Finance Research Letters 22 (2017) 163–168

Contents lists available at ScienceDirect

Finance Research Letters

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

Stock market contagion during the global financial crisis: A multiscale approach

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ARTICLE INFO

Article history:
Received 24 November 2016
Accepted 30 December 2016
Available online 3 January 2017

JEL classification:
G15
G01

Keywords:
Contagion
Stock market
Global financial crisis
Multiscale analysis

ABSTRACT

We propose a multiscale correlation contagion statistic to test for stock market contagion during the global financial crisis (GFC) from the US to the other six G7 and BRIC countries. We find that cross-market correlations between the US and selected countries are conditional on the time scale. Stock market contagion during the GFC is dependent on both the recipient country and the time scale, e.g., contagion from the US to Japan, China, and Brazil occurs when the time scale is longer than 50 days or more. Our findings are important to international investors when they make decisions about global portfolio diversification.

1. Introduction

The global financial crisis (GFC) of 2007–2009 is generally considered the worst financial crisis and the largest economic downturn since the Great Depression of 1929–1939. It has focused the attention of academics and policy-makers who want to better understand financial market contagion. One question is whether the apparent market transmission of the GFC from the US to other countries is actually contagion. Although much effort has been devoted to this topic (see, e.g., Fry-McKibbin et al., 2014; Mollah et al., 2016; Tabak et al., 2016), little attention has been paid to the multiscale (or multi-horizon) effect[1] on financial market contagion. This is an important concern because the trading and investment strategies of market participants vary across the different time scales associated with different trading and investment horizons (Wang et al., 2016).

Here we propose a multiscale correlation contagion test for quantifying stock market contagion during the GFC at different time scales. Our work combines the correlation contagion test proposed by Forbes and Rigobon (2002) (FR) and further refined by Fry et al. (2010) with the multiscale correlation coefficient (MCC) developed by Zebende (2011),[2] where

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[1] The multiscale (or multi-horizon) effect is widely found in finance literature (see, e.g., Gençay et al., 2003; In and Kim, 2006; Kim and In, 2006; Masih et al., 2010; Dewandaru et al., 2016).

[2] The MCC is also known as the detrended cross-correlation coefficient because it is based on the detrended fluctuation analysis (DFA) proposed by Peng et al. (1994) and the detrended cross-correlation analysis (DCCA) developed by Podobnik and Stanley (2008), which are used to detect auto-correlation in a time series and cross-correlation between two time series, respectively.

http://dx.doi.org/10.1016/j.frl.2016.12.025

the former is based on adjusted correlation coefficients by taking account of the heteroskedasticity bias due to the changing volatility and the latter can quantify the level of correlation between two time series at different time scales. Forbes and Rigobon (2002) define contagion as "a significant increase in cross-market linkages after a shock to one country (or group of countries)." They also point out that there is no contagion and only interdependence if two markets exhibit a high level of co-movements during both the pre-crisis and crisis periods. Based on the work of Forbes and Rigobon (2002), Fry et al. (2010) propose the *FR* statistic to test for contagion from the source country to the recipient country by comparing the adjusted correlation in the crisis period with the correlation in the pre-crisis period. By introducing multiscale correlation analysis, we extend their research and develop a multiscale *FR* statistic to investigate whether stock market contagion during the GFC changes across various time scales. We empirically examine stock market contagion during the GFC from the US to the other six G7 and BRIC countries at different time scales.

Our study contributes to the literature on multiscale correlation measurements for contagion. Gallegati (2012) proposes a wavelet-based multiscale correlation method to test for stock market contagion during the US subprime crisis. Ranta (2013) uses this approach to analyze contagion among world stock markets during different crisis episodes. Reboredo et al. (2014) introduce the MCC to study contagion between oil prices and exchange rates of USD. da Silva et al. (2016) investigate the contagion effect of the 2008 financial crisis between the G7 countries (in terms of GDP) using the MCC. However this literature focuses only on correlation changes between the pre-crisis and crisis periods at different time scales and ignores the heteroskedasticity bias noted by Forbes and Rigobon (2002) because cross-market correlation coefficients are conditional on market volatility. By considering the heteroskedasticity bias, our proposed multiscale correlation contagion test differs from the above research and contributes to the contagion literature from a multiscale point of view.

The rest of this paper is organized as follows. In Section 2 we introduce the proposed multiscale correlation contagion test. In Section 3 we present the data and empirical results. We draw our conclusions in Section 4.

2. Multiscale correlation contagion test

The object of the multiscale correlation contagion test is to study financial market contagion during a financial crisis from a source country to a recipient country at different time scales. Our proposed test is based on the MCC introduced by Zebende (2011) and the correlation contagion test framework developed by Forbes and Rigobon (2002) and Fry et al. (2010). In what follows, we first introduce the MCC method for calculating cross-market correlation coefficients at different time scales, and then develop the multiscale *FR* statistic to test for contagion.

Consider two stock market returns $\{r_X(t)\}$ and $\{r_Y(t)\}$ of countries X and Y with the same length N. We integrate the two returns into two profiles, $R_X(k) = \sum_{t=1}^{k} r_X(t)$ and $R_Y(k) = \sum_{t=1}^{k} r_Y(t)$, where $k = 1, 2, \ldots, N$. Both profiles are split into $N-n$ overlapping boxes with an equal length $n+1$. In each box from i to $i+n$ we define the local trends as $\tilde{R}_X^i(k)$ and $\tilde{R}_Y^i(k)$ $(i \le k \le i+n)$, which are estimated by the linear least-squares fitting of $R_X(k)$ and $R_Y(k)$. The "detrended walk" (or residual) is defined as the difference between the original walk (i.e., $R_X(k)$ or $R_Y(k)$) and the local trend (i.e., $\tilde{R}_X^i(k)$ or $\tilde{R}_Y^i(k)$). The covariance of the residuals in each box is defined as $\mathrm{Cov}_{XY}(n,i) = 1/(n-1)\sum_{k=1}^{i+n}(R_X(k) - \tilde{R}_X^i(k))(R_Y(k) - \tilde{R}_Y^i(k))$. By averaging over all $N-n$ boxes of size (scale) n, we obtain the scale-dependent covariance

$$\mathrm{Cov}_{XY}(n) = (N-n)^{-1}\sum_{i=1}^{N-n}\mathrm{Cov}_{XY}(n,i). \tag{1}$$

When the two returns are identical, the scale-dependent covariance reduces to the scale-dependent variance

$$\mathrm{Var}_Z(n) = (N-n)^{-1}\sum_{i=1}^{N-n}\mathrm{Var}_Z(n,i), \quad Z \in \{X, Y\}, \tag{2}$$

where $\mathrm{Var}_Z(n,i) = 1/(n-1)\sum_{k=1}^{i+n}(R_Z(k) - \tilde{R}_Z^i(k))^2$.

Based on the scale-dependent covariance and variance, the multiscale correlation coefficient between two returns is defined

$$\rho_{XY}(n) = \frac{\mathrm{Cov}_{XY}(n)}{\sqrt{\mathrm{Var}_X(n)\mathrm{Var}_Y(n)}}, \tag{3}$$

where $\rho_{XY}(n)$ ranges from -1 and 1 at each time scale n.

The multiscale correlation contagion test developed here follows the framework proposed by Forbes and Rigobon (2002) and further extended by Fry et al. (2010). To test for contagion during the crisis from a source country X to a recipient country Y, we divide the sample of stock market returns into a pre-crisis period and a crisis period, where the sample sizes of the two sub-periods are N_{pre} and N_{c}, respectively. Given a time scale n, correlations between two stock market returns of countries X and Y during the pre-crisis and crisis periods are denoted as $\rho_{\mathrm{pre}}(n)$ and $\rho_{\mathrm{c}}(n)$. To remove the heteroskedasticity bias caused by increasing volatility in stock market returns of the source country during the crisis period, we follow Forbes and Rigobon (2002) and introduce the adjusted correlation coefficient at time scale n, i.e.,

$$\nu_c(n) = \frac{\rho_c(n)}{\sqrt{1+\delta(n)(1-\rho_c^2(n))}}, \tag{4}$$

where the term $\delta(n) = (\mathrm{Var}_{X,c}(n) - \mathrm{Var}_{X,\mathrm{pre}}(n))/\mathrm{Var}_{X,\mathrm{pre}}(n)$ is the relative increase in volatility in stock market returns of the source country *X*, and $\mathrm{Var}_{X,\ \mathrm{pre}}(n)$ and $\mathrm{Var}_{X,\ c}(n)$ are scale-dependent variances of country *X* during the pre-crisis and crisis periods [see Eq. (2)]. Following Fry et al. (2010), we define the multiscale *FR* statistic to test for contagion from country *X* to country *Y*

$$FR^n(X \to Y) = \left(\frac{\upsilon_c(n) - \rho_{\mathrm{pre}}(n)}{\sqrt{\mathrm{Var}(\upsilon_c(n) - \rho_{\mathrm{pre}}(n))}} \right)^2, \tag{5}$$

where

$$\mathrm{Var}(\upsilon_c(n) - \rho_{\mathrm{pre}}(n)) = \mathrm{Var}(\upsilon_c(n)) + \mathrm{Var}(\rho_{\mathrm{pre}}(n)) - 2\mathrm{Cov}(\upsilon_c(n), \rho_{\mathrm{pre}}(n)), \tag{6}$$

$$\mathrm{Var}(\upsilon_c(n)) = \frac{(1+\delta(n))^2}{2\left[1+\delta(n)(1-\rho_c^2(n))\right]^3} \left[\frac{(2-\rho_c^2(n))(1-\rho_c^2(n))^2}{N_c} + \frac{\rho_c^2(n)(1-\rho_c^2(n))^2}{N_{\mathrm{pre}}} \right], \tag{7}$$

$$\mathrm{Var}(\rho_{\mathrm{pre}}(n)) = \frac{1}{N_{\mathrm{pre}}}(1-\rho_{\mathrm{pre}}^2(n))^2, \tag{8}$$

$$\mathrm{Cov}(\upsilon_c(n), \rho_{\mathrm{pre}}(n)) = \frac{1}{2N_{\mathrm{pre}}} \frac{\rho_c(n)\rho_{\mathrm{pre}}(n)(1-\rho_c^2(n))(1-\rho_{\mathrm{pre}}^2(n))(1+\delta(n))}{\sqrt{\left[1+\delta(n)(1-\rho_c^2(n))\right]^3}}. \tag{9}$$

According to Fry et al. (2010), under a null hypothesis of no contagion the multiscale *FR* test for contagion is asymptotically distributed as $FR^n(X \to Y) \xrightarrow{d} \chi_1^2$. If $FR^n(X \to Y)$ is larger than the critical value of χ_1^2 at a given significance level α, contagion occurs from the source country *X* to the recipient country *Y* at time scale *n*. In our study, the significance level α is set at 5% and the corresponding chi-square critical value is 3.84.

3. Data and empirical results

We use data comprising daily closing prices of stock market indices of the G7 and BRIC countries, i.e., S&P 500 (US), S&P TSX (Canada), CAC 40 (France), DAX 30 (Germany), FTSE MIB (Italy), NIKKEI 225 (Japan), FTSE 100 (UK), BOVESPA (Brazil), MICEX (Russia), BSE SENSEX (India), and SSE (China). We focus on the GFC of 2007–2009 triggered in the US. We collect data in local currencies during the period from 1 January 2002 to 31 December 2009, available from Datastream.[3] The choice of the sample period follows Fry-McKibbin et al. (2014) who use a regime switching model to identify different crisis dates in the period of September 1995–January 2013 and find that the non-crisis period for the GFC extends from January 2002 to July 2007 and the crisis period from July 2007 to December 2009. Thus we separate period into two sub-periods, the pre-crisis period starting from 1 January 2002 to 29 June 2007 with 1434 observations and the crisis period from 2 July 2007 to 31 December 2009 with 654 observations. Following Forbes and Rigobon (2002), we employ two-day rolling-average returns to eliminate the non-synchronous trading effect in world stock markets.[4] Prior to computing the statistic for the contagion test, we follow Hon et al. (2004) and Mollah et al. (2016) and use a 2-variate VAR model with five lags to filter out any possible serial autocorrelation in stock market returns between the source country (i.e., the US) and each recipient country during each sub-period. The residuals from the VAR are used to test for contagion as described in Section 2.[5]

For the sake of comparison, we use the *FR* statistic of Fry et al. (2010) to test for contagion during the GFC from the US to other selected countries. Table 1 shows cross-market correlation coefficients between the US and other selected countries during the pre-crisis and crisis periods and the values of the *FR* statistic. During the pre-crisis period the US is highly correlated with the other G7 countries (except for Japan) and Brazil and much less correlated with the remaining BRIC countries (i.e., Russia, India, and China). During the crisis period, cross-market correlations between the US and all other countries significantly increase, suggesting that there are distinct stock market co-movements during the GFC, but that the order of strength of cross-market correlations is similar to that during the pre-crisis period, and the correlation with China remains the smallest. The *FR* statistics show that there is clearly contagion during the GFC from the US to the other G7 countries (except for Japan) and two BRIC countries (i.e., Russia and India) and no contagion from the US to Brazil, China, and Japan. Although Brazil is highly correlated with the US and are both located in the same region, no contagion occurs from the US to Brazil, and only interdependence exists between them.

Fig. 1 shows multiscale correlation coefficients between the US and other selected countries for both the pre-crisis and crisis periods. We find that the correlation coefficients for ten pairs of countries in either the pre-crisis or crisis periods are

[3] The choice of using local currencies follows Mink (2015) who investigates whether to use the local or common currency returns to study stock market contagion and argues that using returns denominated in local currencies is more appropriate because the local currency returns accurately reflect the price fluctuations of national stock markets.

[4] The daily stock market return of country *X* is defined as $r_X(t)$=100ln($P_X(t)/P_X(t$ - 1)), where $P_X(t)$ is the price of stock market index of country *X* on day *t*. To test the robustness we use daily returns as an alternative contagion test and find that the results are consistent with our central findings, which are similar to those in Forbes and Rigobon (2002).

[5] That is to say, we use the residuals from the VAR to replace the returns when computing the multiscale *FR* statistic described in Section 2.

Table 1
Test for stock market contagion during the global financial crisis from the US (X) to selected countries (Y).

Country (Y)	ρ_{pre}	ρ_c	$FR(X \to Y)$	Contagion?
Canada	0.692	0.767	80.708	C
France	0.589	0.713	35.739	C
Germany	0.649	0.735	68.305	C
Italy	0.564	0.667	40.873	C
Japan	0.164	0.302	0.074	N
UK	0.515	0.690	12.252	C
Brazil	0.505	0.770	0.020	N
Russia	0.130	0.396	6.163	C
India	0.075	0.377	13.966	C
China	0.016	0.066	0.247	N

Notes: This table reports the correlation contagion test proposed by Forbes and Rigobon (2002) and further extended by Fry et al. (2010). ρ_{pre} and ρ_c are cross-market correlation coefficients between the US and the selected country during the pre-crisis period and the crisis period, respectively. The pre-crisis period is defined as 1 January 2002 to 29 June 2007. The crisis period is defined as 2 July 2007 to 31 December 2009. $FR(X \to Y)$ is the Forbes-Rigobon (FR) statistic for contagion test proposed by Fry et al. (2010). $FR(X \to Y) \xrightarrow{d} \chi_1^2$. The symbol "C" ("N") means that the FR contagion statistic is larger (less) than the chi-square critical value at 5% significance level and thus (no) contagion occurs from the US to the selected country. The chi-square critical value at 5% significance level is 3.84.

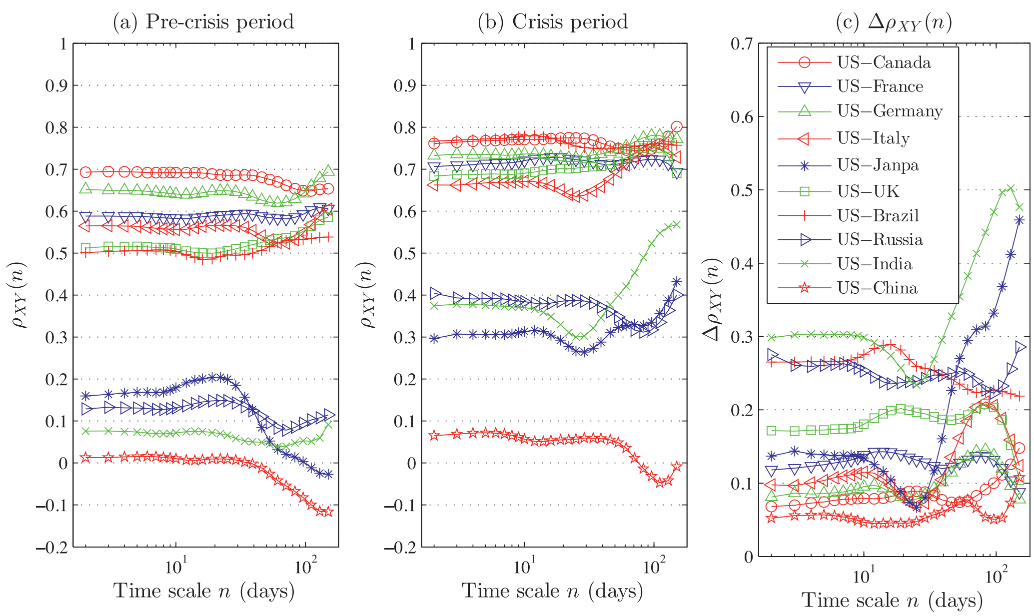

Fig. 1. Multiscale correlation coefficients $\rho_{XY}(n)$ between the US stock market and other 10 markets from the other six G7 and BRIC countries (a) for the pre-crisis period and (b) for the crisis period. Panel (c) shows the variable $\Delta\rho_{XY}(n)$ that is defined as the difference of $\rho_{XY}(n)$ between the pre-crisis period and the crisis period.

conditional on the time scale and that cross-market correlations (i) are stable at small time scales ($n < 10$ days), (ii) some fluctuate when $10 < n < 40$, and (iii) all rapidly rise or drop when $n > 40$. Depending on the level of multiscale correlation of the coefficients, the selected ten countries in the pre-crisis period fall into two categories: (i) highly correlated countries with the US including the other G7 countries (but excluding Japan) and Brazil, and (ii) weakly correlated countries with the US including Japan and three BRIC countries other than Brazil. For different time scales, cross-market correlations between the US and all other countries increase significantly during the crisis period but the increasing intensity of US–China is relatively small. To observe the changes in cross-market correlations, we introduce the variable $\Delta\rho_{XY}(n)$, defined as the difference of $\rho_{XY}(n)$ between the pre-crisis and crisis periods. Fig. 1(c) shows that all $\Delta\rho_{XY}(n)$ values are positive and vary across time scales, indicating significant stock market co-movements at different time scales, especially when the time scales are long. Overall, cross-market correlations between the US and other selected countries have a multiscale (or multi-horizon) effect.

To test whether multiscale behavior affects contagion, we employ the FR statistic to test for contagion during the GFC from the US to other selected countries at different time scales. Fig. 2 shows multiscale correlation contagion tests for ten

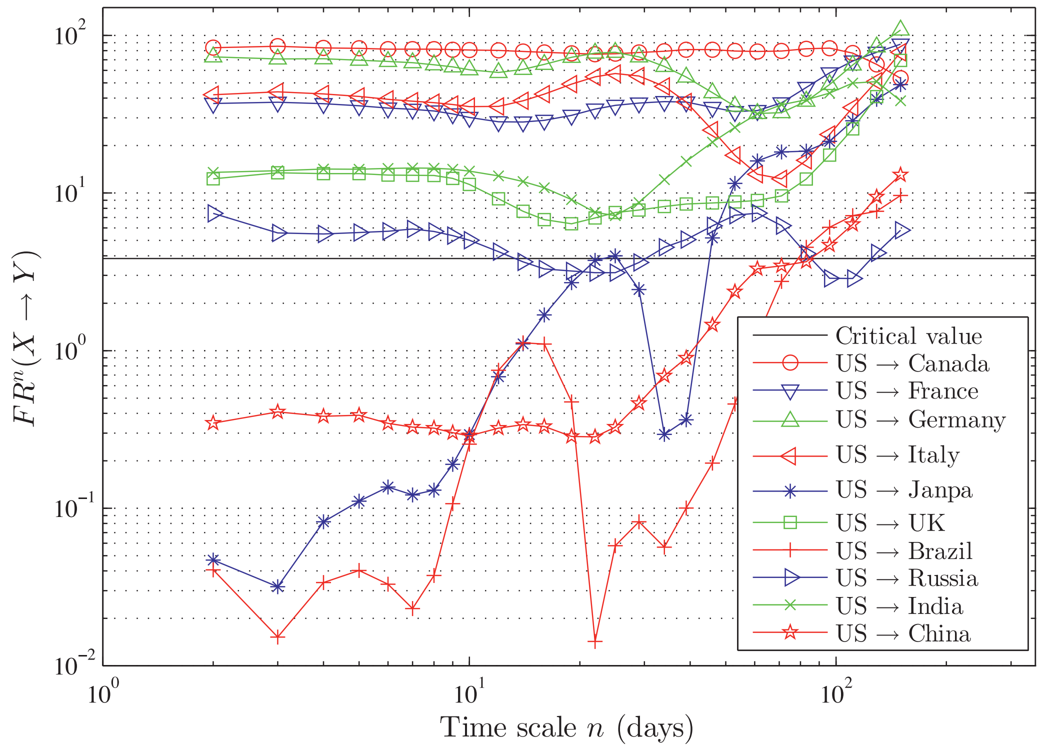

Fig. 2. Multiscale *FR* statistic tests for stock market contagion during the global financial crisis (GFC) from the US to the other six G7 and BRIC countries at different time scales. $FR^n(X \to Y) \xrightarrow{d} \chi_1^2$. The solid back line is the chi-square critical value (3.84) at 5% significance level. If the value of $FR^n(X \to Y)$ is greater than the critical value, contagion occurs during the GFC from country X (i.e., the US) to country Y at time scale n.

pairs of countries. The solid line is the chi-square critical value (i.e., 3.84) at a 5% significance level. Similar to multiscale correlation coefficients, the multiscale *FR* statistics change across time scales, meaning that contagion has a multiscale effect. The values of $FR^n(X \to Y)$ for US → Canada, US → Germany, US → Italy, US → France, US → India, and US → UK are always greater than the chi-square critical value at different time scales, which suggests that contagion occurs during the GFC from the US to the above six recipient countries at all time scales. The multiscale *FR* statistic for US → Russia moves up and down the chi-square critical value and is larger than 3.84 for most time scales, indicating that contagion does not always occur from the US to Russia and that there is only interdependence between them at some time scales. When time scale $n < 50$ days or more, multiscale *FR* statistics for US–Japan, US–China, and US–Brazil are less than 3.84, suggesting that no contagion occurs from the US to these three countries, and this is consistent with the conclusion obtained by the *FR* statistic reported in Table 1. However when $n > 50$ days (approximatly two trading months) for US → Japan and $n > 70$ days (approximately three trading months) for US → China and US → Brazil, their corresponding $FR^n(X \to Y)$ values are greater than 3.84, indicating that contagion occurs during the GFC from the US to Japan (when time scale $n > 50$ days), China, and Brazil (when $n > 70$ days). The Chinese stock market experienced a two-year bull market during the period from 6 June 2005 to 16 October 2007 and the SSE index increased 489% from 1086 points to 6396 points. This was immediately followed by a one-year bear market in China during the period 17 October 2007–28 October 2008, and the SSE index dropped 71% from 6337 points to 1807 points. One possible reason for China's bear market could have been the strong influence of the spreading US subprime crisis. Note that the break date between the bull and bear markets is 17 October 2007, which is approximately 77 trading days behind the breakpoint of the GFC set in our study. This supports our finding that contagion occurs during the GFC from the US to China when the time scale is larger than 70 days. Our findings concerning Japan, China, and Brazil are not detected by the correlation contagion test of Forbes and Rigobon (2002) and Fry et al. (2010), and thus our findings are a significant contribution to the contagion literature. Overall, the occurrence of stock market contagion during the GFC depends not only on the recipient country but also on the time scale.

4. Conclusion

We have proposed a multiscale *FR* statistic for investigating stock market contagion during the GFC from the US to the other six G7 and BRIC countries. We have found that cross-market correlations during both the pre-crisis and crisis periods are conditional on the time scale. Cross-market correlations at different time scales during the crisis period increase significantly. For all time scales, contagion occurs during the GFC from the US to the other five non-US and non-Japan G7 countries and India. Contagion during the GFC from the US to Russia depends on the time scale and there is only interdependence between them at some time scales. Contagion occurs from the US to Japan, China, and Brazil when the time scale is $n > 50$ days or more.

Our findings have important implications for international portfolio diversification. International investors should take into account the multiscale (or multi-horizon) effect of cross-market correlations and contagion when they construct global asset portfolios. The increased correlations during the financial crisis can reduce the benefits of global portfolio diversification. In particular, investors should pay attention to the multiscale contagion that propagates from the US to the other five non-US and non-Japan G7 countries and India because the potential diversification gains between the US and these countries can disappear. No contagion propagates from the US to China and Japan, and their low correlations at short time scales may offer new opportunities in cross-market portfolios.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant nos. 71501066 and 71373072), the China Scholarship Council (Grant no. 201506135022), the Specialized Research Fund for the Doctoral Program of Higher Education (Grant no. 20130161110031), and the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (Grant no. 71521061). The Boston University work was supported by NSF Grants PHY-1505000, CMMI-1125290, and CHE-1213217, and by DTRA Grant HDTRA1-14-1-0017 and DOE Contract DE-AC07-05Id14517.

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