Volatility spillovers between foreign exchange and stock markets in industrialized countries

Amalia Morales-Zumaqueroa and Simón Sosvilla-Riverob[1]*

aDepartment of Economic Theory and History, Universidad de Málaga, 29071 Málaga, Spain

bComplutense Institute for International Studies, Universidad Complutense de Madrid. 28223 Madrid, Spain

Abstract

This paper empirically analyses the evidence of intra-spillovers and inter-spillovers between foreign exchange and stock markets in the seven economies which constitute the majority of foreign exchange transactions (i.e. the United Kingdom, the United States, the Euro area, Australia, Switzerland, Canada, and Japan). Daily data during the period 1 January 1990 to 31 December 2015 and during the pre-global and post-global financial crisis periods is used. To that end, we employ two econometric methodologies: the C-GARCH methodology and the SVAR framework. Results suggest that: (i) permanent and transitory components of the conditional variance exhibit peaks in volatility during episodes of growing economic and financial instability; (ii) the long-run volatility relationships are stronger than the short-run volatility linkages with a reinforcement during the post-global financial crisis period; (iii) the presence of intra-spillovers and inter-spillovers increases substantially during the post-global financial crisis period and (iv) the stock markets play a dominant role in the transmission of long-run and short-run volatility in all samples, except for the period after the global financial crisis, where the foreign exchange markets are the main long-run volatility triggers.

Keywords: Stock markets, Exchange rates, Market spillovers, Component-GARCH model, Long-run volatility, Short-run volatility.

JEL Classification Codes: C32, F31, G15.

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[1]*Corresponding author. Tel.: +34 913942342; fax: +34 913942591.

E-mail addresses: amalia@uma.es (A. Morales-Zumaquero), sosvilla@ccee.ucm.es (S. Sosvilla-Rivero)

1. Introduction

Economic and financial globalization generates intense co-movement across countries. Mutual relations between foreign exchange markets and stock markets have attracted a lot of attention from researchers and academics since the beginning of the 1990s, particularly because this influence can help to explain some excess variability in foreign exchange markets, since significant pricing errors have a tendency to develop in equity markets [see, for example, Shiller (1981) and Campbell and Shiller (1987)].Two theoretical approaches have been proposed in the literature to explain the interdependence between stock prices and exchange rates, namely the flow-oriented models and the stock-oriented models, which provide conflicting results on both the existence of the relationship between stock prices and exchange rates and the direction of the relationship. The flow-oriented approach suggests that exchange rates will affect stock prices because they affect the trade balance and the competitiveness of domestic products, thus influencing output and real income; as stock prices reflect the present value of estimated future income, fluctuations in the exchange rate drive fluctuations in the stock price. Therefore, flow-oriented models claim a positive linkage between the exchange rate and the stock prices with the direction of causation running from the exchange rates to the stock prices (see, e.g. Dornbusch and Fischer, 1980). Alternatively, the stock-oriented approach emphasizes the role of the financial account in the determination of the exchange rates. Broadly speaking, two types of stock-oriented models can be identified: the portfolio balance and monetary models. Portfolio balance models postulate a negative relationship between stock prices and exchange rates and come to the conclusion that stock prices have an impact on exchange rates (see, for example, Frankel, 1983; Branson and Henderson, 1985; or Black, 2015). Such models suggest that innovations in the stock market would have an impact on wealth and liquidity, thus influencing the demand on money and exchange rates. The monetary approach to exchange rate determination emerged as the dominant exchange rate model at the outset of the recent float in the early 1970s and remains an important exchange rate paradigm (Frenkel, 1976; Mussa, 1976; Bilson, 1978)[2]. According to the forward looking monetary model of exchange rate determination, the exchange rate is assimilated into financial asset prices and therefore the exchange rate dynamics is determined by all the relevant macroeconomic factors affecting the anticipated value (Macdonald and Taylor, 1993). Since both exchange rates and stock prices may be influenced by a number of common factors, these "stock-oriented" exchange rate models suggest that there is no linkage between exchange rates and stock prices (Gavin, 1989).

Evidence of strong relationship between the two markets is instructive for domestic policy making and portfolio reallocation because shocks to either market may be transmitted quickly to another or to the domestic economy through various contagious channels (see, e. g., Sensoy and Sobaci, 2014 and Leung et al., 2017). The interdependence of stock price returns and exchange rate changes has been extensively examined in the empirical literature with mixed findings on the directional causality[3]. Likewise, empirical evidence on the dynamic linkage between stock and currency market volatilities also provides conflicting findings. Early studies, such as Jorion (1990), suggested that exchange rate fluctuations do not affect stock return volatility, while others (see, for example, Engle, Ito and Lin (1990), Dumas and Solnik, 1995; Roll, 1992) identified the existence of a strong linkage. More recently, Kanas (2000) analyses volatility transmission between stock and currency markets in the USA, the UK, Japan, Germany, France and Canada and found evidence of spillovers between stock returns and exchange rate changes for five of the six countries analysed (with Germany being the exception). Yang and Doong (2004)

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[2] The monetary approach starts from the definition of the exchange rate as the relative price of two monies and attempts to model that relative price in terms of the relative supply of and demand for those monies. The second building block of the monetary model is absolute purchasing power parity, which holds that goods-market arbitrage will tend to move the exchange rate to equalize prices in two countries. The domestic money supply determines the domestic price level and hence the exchange rate is determined by relative money supplies. The model further assumes that the uncovered interest parity condition holds and, under rational expectations, the exchange rate is therefore determined by the expected values of the fundamental variables.

[3] See Adler and Dumas, 1984; Booth and Rotenberg, 1990; Jorion, 1990; Jorion, 1991; Sercu and Vanhulle, 1992; Smith 1992; Bahmani-Oskooee and Sohrabian, 1992; Bodnar and Gentry, 1993; Bartov and Bodnar, 1994; Choi and Prasad, 1995; Ajayi and Mougoue, 1996; Chow et al., 1997; Abdalla and Murinde, 1997; He and Ng, 1998; Nieh and Lee, 2001; Granger et al., 2000; Smyth and Nandha, ,2003; Hatemi-J and Irandoust, 2005; Pan et al., 2007; and Inci and Lee, 2014; among others.

investigated volatility spillovers between stock prices and exchange rates for the G-7 countries with the finding that stock markets play a relatively more important role than foreign exchange markets in the second moment interactions and spillovers. Wang et al. (2013) use a dependence-switching copula model to describe the dependence structure between the stock and foreign exchange markets for six major industrial countries (Canada, France, Germany, Italy, Japan and the United Kingdom) over the 1990–2010 period concluding that the dependence and tail dependence among the above market statuses are asymmetric for most countries in the negative correlation regime, but symmetric in the positive correlation. Beirne and Gieck (2014) assess interdependence and contagion across three asset classes (bonds, stocks, and currencies) for over 60 economies over the period 1998–2011, concluding that in times of financial crisis, US equity shocks lead to risk aversion by investors in equities and currencies globally. Caporale *et al.* (2014) examine the linkages between stock market prices and exchange rates in six advanced economies, finding evidence of unidirectional Granger causality from stock returns to exchange rate changes in the US and the UK, from exchange rate changes to stock returns in Canada, and bidirectional causality in the Euro area and Switzerland. Andreas *et al.* (2014) explore the structure of the volatility transmission mechanism between stock and currency markets for Euro area economies with systemic fiscal problems, presenting evidence for the existence of bidirectional, asymmetric volatility spillovers between currency and stock markets. Finally, Tian and Hamori (2016) study the cross-market financial shock transmission mechanism on the foreign exchange, equity, bond, and commodity markets in the United States using a time-varying structural vector autoregression model with stochastic volatility, finding that the dynamics of volatility spillovers vary tremendously over time.

In this study we will focus on the volatility spillovers between foreign exchange and stock markets[4], since volatility is an important gauge of financial performance, indicating uncertainty or risk and volatility spillovers can provide a measure of the transmission of

[4] Masson (1999) employs the term "spillovers" for effects that arise from macroeconomic interdependence among developing countries, but following Gelos and Sahay (2001), this paper uses the term in a broader sense where a "spillover" is any type of impact on other financial markets

financial stress across the markets. Therefore, our analysis is motivated by the need to better capture and understand the phenomena behind the elusive dynamics of volatility spillovers (namely crashes, distress and contagion), since it seems that the growing interdependence between economies, markets, and asset classes has resulted in increased transmission of negative shocks across markets (see, for example, Wu, 2001). Furthermore, explaining, predicting and understanding the behaviour of volatility is relevant in, portfolio selection, valuation and risk management as well as designing optimal hedging strategies for options and futures (French et al., 1987; Chou, 1988).

Although the analysis of the volatility spillovers could be considered an old question we think it is necessary a further analysis from a different econometric perspective. Thus, this paper investigates the existence of volatility decomposition to assess the strength and direction of the volatility transmission process between the exchange rate and stock markets since previous research suggests that returns volatility may contain both short-run and long-run components due to the existence of heterogeneous information flows or heterogeneous agents (see, e. g., Andersen and Bollerslev 1997a, 1997b; and Müller *et al.*, 1997). Strength is measured through the correlation between the long- and short-term components, while direction is measured through the causality of these components. Our volatility decomposition is also in line with the classification of the transmission channels of volatility shocks proposed by Dornbusch *et al.* (2000): fundamental-based and investor behaviour-based links. While the fundamental-based transmission mechanism works through real and financial linkages across countries, the behaviour-based mechanism is more sentiment-driven. In this study, we relate the first transmission channel with the long-run component of volatility and the second with the short-run component of volatility. Indeed, Engle *et al.* (2008) suggest that the short-run component captures the dynamics of conditional volatility associated with the transitory effects of volatility innovations, while the long-term component characterizes the slower variations in the volatility process associated with persistent effects.

The rest of the paper is organized as follows. Section 2 explains the econometric methodology. The data and empirical results are reported in Section 3. Finally, Section 4 summarizes the findings and offers some concluding remarks.

2. Econometric methodology

This section describes the econometric methodology adopted in this study. We follow three steps in the analysis: First, we decompose time-varying volatility into permanent and transitory components and then we analyse whether there are correlations between the permanent and transitory components of volatility between foreign exchange and stock markets. Second, under the SVAR framework, we analyse whether volatility spills over between the markets reciprocally. Third, we use the Granger causality approach to assess whether there is evidence in favour of bidirectional or unidirectional causality.

2.1 C-GARCH model

Engle and Lee (1999) proposed a "component-GARCH" (C-GARCH) model to decompose time-varying volatility into a permanent (long-run) and a transitory (short-run) component. The C-GARCH is a superior volatility model for exchange rate and stock markets, being widely used in finance (see Christoffersen *et al*., 2008).[5]

Consider the original GARCH model:

$$\sigma_t^2 = \omega + \alpha(\varepsilon_{t-1} - \omega) + \beta(\sigma_{t-1}^2 - \omega) \tag{1}$$

As can be seen, the conditional variance of the returns has mean reversion to some time-invariable value, ω . The influence of a past shock eventually decays to zero as the volatility converges to this value according to the powers of ($\alpha + \beta$)[6]. The standard GARCH

[5] Following Christoffersen *et al*. (2008), some of the advantages of the C-GARCH model are: (i) the empirical performance of the variance component model is significantly better than that of the benchmark GARCH(1,1) model, in-sample as well as out-of-sample; (ii) the information used in estimation; (ii) it has a richer parameterization that allows for improved joint modeling of long-maturity and short-maturity options.

[6] This is true only if + is strictly smaller than zero.

model therefore makes no distinction between the long-run and short-run decay behaviour of volatility persistence.

For the permanent specification, the C-GARCH model replaces the time-invariable mean reversion value, ω, of the original GARCH formulation in equation (1) with a time variable component q_t:

$$q_t = \hat{\omega} + \rho(q_{t-1} - \hat{\omega}) + \varphi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) \tag{2}$$

Here, q_t is the long-run time-variable volatility level, which converges to the long-run time-invariable volatility level $\hat{\omega}$ according to the magnitude of ρ. This permanent component thus describes the long-run persistence behaviour of the variance. The long-run time-invariable volatility level $\hat{\omega}$ can be viewed as the long-run level of returns variance for the relevant sector when past errors no longer influence future variance in any way. Stated differently, the value $\hat{\omega}$ can be seen as a measure of the 'underlying' level of variance for the respective series. The closer the estimated value of ρ in equation (2) is to one, the slower q_t approaches $\hat{\omega}$, and the closer it is to zero the faster it approaches $\hat{\omega}$. The value ρ therefore provides a measure of the long-run persistence.

The second part of the C-GARCH model is the specification for the short-run dynamics, the behaviour of the volatility persistence around this long-run time-variable mean, q_t:

$$\sigma_t^2 - q_t = \gamma(\varepsilon_{t-1}^2 - q_{t-1}) + \lambda(\sigma_{t-1}^2 - q_{t-1}) \tag{3}$$

According to this transitory specification, the deviation of the current condition variance from the long-run variance mean at time t ($\sigma_t^2 - q_t$) is affected by the deviation of the previous error from the long-term mean $(\varepsilon_{t-1}^2 - q_{t-1})$ and the previous deviation of the condition variance from the long-term mean $(\sigma_{t-1}^2 - q_{t-1})$. Therefore, in keeping with its GARCH theoretical background, the C-GARCH specification continues to take account of the persistence of volatility clustering by having the conditional variance as a function of past errors. As the transitory component describes the relationship between the short-run and long-run influence decline rates of past shocks, values of ($\gamma+\lambda$) closer to one imply slower convergence of the short-run and long-run influence decline rates, and values closer to zero the opposite. The value ($\gamma+\lambda$) is therefore a measure of how long this non-long-run (i.e. short-run) influence decline rate is.

Together, these two components of the C-GARCH model describe, just like the original GARCH formulation, how the influence of a past shock on future volatility declines over time. However, with the C-GARCH model, this persistence is separated into a short-run and long-run component, along with the estimation of the underlying variance level once the effect of both components has been removed from a series. The long-run (permanent) component provides a measure of volatility generated by fundamental factors [see, for example, Blake and McMillan (2004) and Byrne and Davis (2005)], while the short-run (transitory) component represents mostly transitory volatility conditioned by financial market considerations, such as the arrival of new information, speculation and hedging positions. [7]

2.2. *SVAR framework*

We consider the variance causality among the estimated volatility components in a structural Vector Auto-Regression (SVAR) framework (Azad *et al.*, 2015). [8] Following Bollerslev (1990) under this multivariate regression framework, the models can be thought of as an extension of Seemingly Unrelated Regression (SUR) and thus, the models are estimated in a SUR framework.

We distinguish between intra-spillover and inter-spillover models. In the first kind of model, we analyse the evidence of spillovers between foreign exchange and stock markets inside a country. In the second kind of model, we study the evidence of spillovers between foreign exchange and stock markets but across countries.

[7] There is a vast literatura showing how financial markets respond systematically to news regarding fundamental and, in this context, the short-run component would be driven by fundamentals and sentiment (non-fundamentals factors) (see, e. g., Ederington and Lee, 1993; Engle and Ng, 1993; and McQueen and Roley, 1993).

[8] We choose the two stage approach with the GARCH modelling followed by the VAR, rather than a VAR-MGARCH model for computational convenience, given the large number of parameters to estimate.

2.2.1. Intra-spillover models

2.2.1.1. Long-run intra-spillover models

Under this framework we estimate two equations for each of the countries under study. In the case of the United States the equations are as follows:

Cargando… (4a)[9]

Cargando… (4b)

where Cargando… is the long-run component of volatility in the stock market and Cargando… is the long-run component of volatility in the foreign exchange market. To test for long-run volatility spillovers we check whether the coefficients Cargando…and Cargando…, of equations (4a) and (4b) respectively, are statistically significant or not.

2.2.1.2. Short-run intra-spillover models

In the short-run framework and selecting for example, for the United States, the two equations to estimate are:

Cargando… (5a)

Cargando… (5b)

where Cargando… is the short-run component of volatility in the stock market and Cargando… is the short-run component of volatility in the foreign exchange market. To test for short-run volatility spillovers we check whether the coefficients Cargando… and Cargando…, of equations (5a) and (5b) respectively, are statistically significant or not.

2.2.2. Inter-spillover models

2.2.2. Inter-spillover models

[9] Following Azad *et al.* (2015) we capture the spillover between foreign exchange and stock markets in a contemporaneous sense. For example, we focus on how the volatility in foreign exchange market in previous period affects the volatility of stock market in period *t* (and *vice versa*).

2.2.2.1. Long-run inter-spillover models

Similarly as in the case of intra-spillovers, we analyse the volatility spillovers across countries using the following models (for example, for the Unites States):

Cargando… (6a)

Cargando… (6b)

where Cargando… are the long-run components of volatility in the foreign exchange markets for the seven countries under study and Cargando… are the long-run components of volatility in the stock markets for the seven countries under study. To test for the long-run volatility spillovers between the United States and Australia for example, we check whether the coefficients Cargando… and Cargando… , of equations (6a) and (6b) respectively, are statistically significant or not.

2.2.2.2. Short-run inter-spillover models

For the case of short-run inter-spillovers, the models to estimate in the case of the United States are as follows:

Cargando… (7a)

Cargando… (7b)

where Cargando… are the short-run components of volatility in the foreign exchange markets for the seven countries under study and Cargando…are the short-run components of volatility in the stock markets for the seven countries under study. Again, to test for the short-run volatility spillovers between the United States and Australia for example, we check whether the coefficients Cargando… and Cargando… , of equations (7a) and (7b) respectively, are statistically significant or not. To that end, the *t*-statistic, which is computed as the ratio of an estimated coefficient to its standard error, is used to test the hypothesis that a coefficient is equal to zero.

2.3. Granger causality

Finally, we complete the previous analysis with the Granger causality approach. The concept of Granger-causality was introduced by Granger (1969) and Sims (1972) and is widely used to ascertain the importance of the interaction between two series. This is based on the time series notion of predictability (Hoover, 2001): given two variables, variable *X* causes variable *Y* if the present value of *Y* can be predicted more accurately by using the past values of *X* and *Y* than by using only past values of *X*.

To test for Granger causality between two series *Y* and *X,* we run bivariate regressions of the form:

Cargando… (8a)

Cargando… (8b)

for all possible pairs in the series (*Y*, *X*) and report the Wald statistics for the joint hypothesis: $\delta_1 = \delta_2 = ... = \delta_m = 0.$ The null hypothesis is that does not Granger-cause in the first regression (8a) and that does not Granger-cause in the second regression (8b).

3. Data and empirical results

3.1 Data

The data consists of daily closing stock prices denominated in local currency for the US (Standard & Poor's 500 composite index, S&P500), the Euro area (Eurostoxx 50 Index), Japan (Nikkei 225 index), the UK (Financial Times Stock Exchange 100 Index, FTSE100), Australia (All Ordinaries Index, AOI), Switzerland (Swiss Market Index, SMI) and Canada (Toronto Stock Exchange Composite Index, TSX). The exchange rate series for each country is a trade-weighted exchange rate, to account for each country's diverse investment positions in foreign equities. In particular, we examine the following effective exchange rates: US Dollar (USD), Euro (EUR), Australian dollar (AUD), Swiss franc (CHF), Canadian dollar (CAD), British pound (GBP) and Japanese yen (JPY). The stock price data has been extracted from Datastream. The exchange rate series are the Bank of England trade-weighted exchange rates. Note that by focusing on these seven major world economies, we cover 174.9% of the global foreign exchange market turnover[10].

Our data covers the period 1 January 1990 to 31 December 2015. In order to assess the possible effect of the Global Financial Crisis (GFC), in addition to the full sample period, we also consider two sub-periods: pre-GFC (1 January 1990 to 8 August 2007) and post-GFC (9 August 2007 to 31 December 2015) in our estimations. The breakpoint date has been fixed at 9 August 2007 when BNP Paribas, France's largest bank, halted redemptions on three investment funds, triggering the active phase of the crisis.

3.2. Empirical Results[11]

3.2.1. Permanent and transitory components

In order to have a visual representation of the role played by the two volatility components of the conditional variance, Figures 1 to 3 plot the time evolution of the total volatility and the estimated transitory and permanent components of volatility for the full sample, the pre-GFC and the post-GFC, respectively[12]. In general, the plots indicate that the permanent component has smooth movements and approaches a moving average of the GARCH volatility, while the transitory component responds largely to market fluctuations, tracking much of the variation in conditional volatility. Consistent with the findings of Engle and Lee (1999), Alizadeh *et al.* (2002) and Brandt and Jones (2006), we show that the long-run component is characterised by a time varying but highly persistent trend, while the short run component is strongly mean-reverting to this trend. For all countries and periods, the temporary component of volatility is much smaller than the permanent component, suggesting that transitory shifts in market sentiment tend to be

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[10] Average of currency distribution of global foreign exchange market turnover over 2001, 2004, 2007, 2010, 2013 and 2016 Bank for International Settlements (2016). Due to the fact that two currencies are involved in each transaction, the sum of the percentage shares of individual currencies totals 200% instead of 100%.

[11] We summarize the results by pointing out the main regularities. The reader is asked to browse through Tables 1 to 9 and Figures 1 to 3 to find evidence for a particular country, market or group of countries or markets of their special interest.

[12] To save space, the estimation results for the C-GARCH models are not shown here, but available from the authors upon request.

less important determinants of volatility than shocks to the underlying fundamentals. Yet, relative to its lower mean level, the transitory component is, in all cases, much more volatile than the long-run trend level of volatility, as one would expect.

[Insert Figures 1 to 3 here]

In these graphs, we observe several peaks in volatilities which coincide with episodes of increasing economic and financial instability: i) the tensions in the European Exchange Rate Mechanism (ERM) in September 1992; ii) the global stock market crash in October 1997 caused by an economic crisis in Asia; iii) the Russian financial crisis in August 1998; iv) the Lehman Bros. demise in September 2008 and v) the European Debt crisis in May 2010.

3.2.2. Correlations between permanent components

In this Section we report the estimated correlations between the permanent component results for the full sample (1 January 1990 to 31 December 2015).[13] If we first focus on the results for the relationships between the stock markets, we observe positive correlations ranking from 0.4558 (AOI and SWI) to 0.8886 (FTSE100 and S&P500). It is noteworthy that the USA stock market is highly correlated with the other six stock markets (with correlations oscillating between 0.7127 and 0.8886).

In the relationships between foreign exchange markets, we find that the correlations although positive are much weaker than in the stock markets, ranging from 0.0627 (AUD and CHF) to 0.7395 (AUD and CAD). We notice a weak correlation between the CHF and the rest of the currencies under study that may be related to its safe-haven characteristics (Grisse and Nitschka, 2015).

The estimated correlations coefficients from the relationship between the domestic currency and the national stock market, are always positive. The higher correlations are found in Canada (0.8291), Australia (0.6816) and Japan (0.6023), followed by the UK (0.5797), the USA (0.4408), the Euro area (0.3697) and Switzerland (0.2890).

[13] Tables with correlation matrix results are available upon request.

Our results show that there are positive correlations in the cross relationships between the stock and foreign exchange markets, but they are weaker than in stock markets and similar to the evidence obtained for the currency markets, ranking from 0.0477 (CHF and NIKKEI 225) to 0.8428 (AUD and S&P500). Once again, the CHF presents a weak correlation with all foreign stock markets. Interestingly, in four out of the six cases under study, the correlation for the AUD, EUR and JPY exchange rates with other stock markets is higher than with the domestic stock market. For the GBP and the USD, this is detected in two and three cases, respectively. Finally, for the CAD and the CHF exchange rates, the correlation with the domestic stock markets is higher than those with the foreign stock markets.

Regarding the estimated correlations between the permanent component results for the pre-GFC sample (1 January 1990 to 8 August 2007), the correlations between stock markets register a substantial decrement by comparison with the values obtained for the full sample, with the only exceptions of the relationships between the EURO STOXX 50 with the SMI, the FTSE100 and the S&P500 and the SMI with the FTSE100. As regards the correlations between foreign markets, they are all once again smaller than those computed for the stock markets (three negative values are observed), and smaller than they were for the full sample. Finally, with reference to the relationship between foreign exchange markets and stock markets, there is evidence of a substantial reduction in the estimated correlations when compared to those obtained for the full sample (with the exception of the CHF with the AOI, EURO STOXX 50 and FTSE100 indices). It is interesting to note that in the cases of the CAD with the AOI and the NIKKEI225, and the CHF with the TSX and the S&P500, the correlations exhibit negative values.

In addition, the estimated correlations between the permanent component results for the post-GFC sample (9 August 2007 to 31 December 2015) suggest, in general, an increase in the estimated correlations both with respect to the full sample period and in particular with respect to the pre-GFC period, although with some exceptions. In regard to the correlations between stock markets, there are important reductions in the correlation, in comparison to those presented before; in the cases of the AOI with all the other stock indices (expect for the FTSE100, where there is an increase in the pre-GFC), the SMI with respect to the FTSE100 and the S&P500 and the FTSE100 with respect to the S&P500. Also note that the AOI presents no negative correlations with respect to the EUROSTOXX nor the NIKEI225. Turning to the case of the correlations between foreign markets, the CHF stands out by experiencing significant drops in comparison to those estimated for both the full sample and the pre-GFC (even registering a negative correlation with respect to the GBP). Finally, as for the correlations between foreign exchange markets and stock markets, the only exception to the general pattern of increased values is once again the CHF which even presents a negative correlation with respect to the FTSE100. A negative correlation is also obtained for the EUR with respect to the AOI.

In summary, our results suggest a reinforcement of the correlation between the stock and foreign markets permanent volatility during the post-GFC period. This finding is consistent with earlier literature in that the linkage between markets intensifies during periods of increasing economic and financial instability (see, for example, Kolb, 2011), implying a loss of diversification just when it is needed most.

3.2.3. Correlations between transitory components

As regards the correlation results between transitory volatility components, we observe a significant reduction in the correlations in all cases when comparing these results with the permanent component results, with the only exception being the relation between the AOI and the TSX for the post-GFC period. Moreover, there are a greater number of negative correlations than in the case of the permanent component of volatility between markets and there are no substantial differences between the pre-GFC and post-GFC periods.

When examining the correlations in the transitory volatility component between stock markets we find negative correlations in 12 out of the 21 cases. The case of the S&P500 stands out since its correlations are always negative except for its relation with Eurostoxx. It is interesting to note that the JPY presents negative correlations with all the other exchange rates under study when regarding the relationships between foreign exchange markets. Finally, in respect to the connections between foreign exchange markets and stock markets, in 21 out of the 49 cases, the estimated correlations are negative, with the cases of the Euro area, Japan and the USA, where we detect negative correlations between the domestic currency and the domestic stock market being especially interesting.

We observe, in the case of the pre-GFC period that in 10 out of 21 cases the correlations between stock markets are negative, which presents negative correlations for the SMI with all markets except with the AOI. The JPY, once again, is the only currency which presents negative correlation values with all other exchange rate markets when examining the correlation between foreign exchange markets. Regarding the correlations between foreign exchange markets and stock markets, in 31 out of the 49 cases, the estimated values are negative, with negative correlations between the domestic currency and the domestic stock market found in four cases (Canada, the Euro area, the UK and the USA).

Finally, and in relation to the post-GFC period, results indicate a negative association between stock markets in 11 out of the 21 considered cases, a negative relation between foreign exchange markets in 14 out of the 21 cases, and a negative interaction between foreign exchange markets and stock markets in 30 out of the 49 cases (those being the correlations between the domestic currency and the domestic stock market in all cases, except for Switzerland).

In summary, our findings suggest that correlations between permanent volatility components are much higher than between transitory volatility components, indicating that in the markets under study, the long run volatility relationships (reflecting the perceived evolution of fundamental factors) are stronger than the short run linkages volatility (incorporating mostly market sentiments and investor behaviour).

3.2.4. Intra-spillovers

3.2.4.1. Full Sample (1 January 1990 to 31 December 2015)

Table 1 displays the results for the full sample. As can be seen, we find evidence of unidirectional spillovers, from the stock markets to the foreign exchange markets, both in long-run and short-run volatility, in the Australian case. For Japan, Switzerland and the UK, our results suggest bidirectional spillovers, both in long-run and short-run volatility, between the stock and foreign exchange markets. For Canada and the Euro area, we find evidence of unidirectional spillovers in the long-run volatility running from the foreign exchange market to the stock market. For Canada we also find evidence of strong unidirectional spillovers in the short-run volatility running from the foreign exchange market to the stock market and weak unidirectional spillovers in the short-run volatility running from the stock market to the foreign exchange market. Finally, our results suggest the presence of unidirectional spillovers, both in long-run and short-run volatility, from foreign exchange markets to stock markets in the USA.

[Insert Table 1 here]

3.2.4.2. Sub-samples: Pre-GFC and post-GFC

As seen in Table 2, for the pre-GFC period (1 January 1990 to 8 August 2007), in general we obtain less evidence of intra-spillovers than in the full sample period. Our results suggest bidirectional spillovers in long-run volatility between the stock and foreign exchange markets for only Switzerland and the UK. For Australia and the Euro area, we find unidirectional spillovers in the long-run volatility running from the foreign exchange market to the stock market. As for the short-run volatility, our results indicate the existence of unidirectional spillovers running from the stock market to the foreign exchange market in Australia, Canada, Japan and Switzerland, as well as bidirectional spillovers between these markets in the Euro area.

[Insert Table 2 here]

For the post-GFC period (9 August 2007 to 31 December 2015), we find evidence of bidirectional spillovers, in both long-run and short-run volatility, between the stock and foreign exchange markets in the cases of Australia and Japan. For Canada and the USA, our results suggest the presence of unidirectional spillovers, both in long-run and short-run volatility, running from the foreign exchange markets to stock markets. Finally for Switzerland we find unidirectional spillovers in long-run and short-run volatility from the foreign exchange markets to stock markets and weak evidence of unidirectional spillovers in short-run volatility from the stock markets to foreign exchange markets.

[Insert Table 3 here]

To sum up, during the pre-GFC there evidence of intra-spillovers between the stock and foreign exchange markets. However, the presence of intra-spillovers increases substantially during the post-GFC period.

3.2.5. Inter-spillovers

3.2.5.1. Full Sample (1 January 1990 to 31 December 2015)

As can be seen in Table 4, for Australia, we find some evidence in favour of inter-spillovers between the Australian stock market and almost all foreign exchange markets in the long-run and short-run. Therefore, external foreign exchange markets contain useful information to explain the evolution of the Australian stock market.

We find some evidence of inter-spillovers in the short-run and in favour of bidirectional causality when regarding the rest of countries (with the exception of Switzerland). The cases of the UK and the USA stand out due to the high percentage of significant spillovers, both in the short-run and the long-run, from external exchange rate markets to domestic stock markets. This finding is in line with the much higher stock market internalization of US and UK companies. Moreover, the high percentage of significant short-run spillovers from the US stock market to external exchange rate markets is consistent with the strong global propagation of US domestic shocks reported by Diebold and Yilmaz (2009).

[Insert Table 4 here]

3.2.5.2. Sub-samples: Pre-GFC and post-GFC

For the pre-GFC period (1 January 1990 to 8 August 2007), comparing the results in Table 5 with those in Table 4, there is little evidence of inter-spillovers in Australia, Canada and the Euro area and some evidence of inter-spillovers in the short-run for Japan, Switzerland and the United States (where the foreign exchange market helps to explain the stock market).

[Insert Table 5 here]

For the post-GFC period (9 August 2007 to 31 December 2015), we find a substantial increment in the evidence in favour of inter-spillovers (Table 6).

[Insert Table 6 here]

In particular, we observe that for Australia there is some evidence of inter-spillovers in the short-run and long-run suggesting that the volatility of external foreign exchange markets is relevant in explaining the volatility of the domestic stock market.

For Canada, we find some evidence in both the long-run and the short-run volatility spillovers from the external exchange rate market to the domestic stock market and bidirectional volatility spillovers in the short-run and long-run with Japan. In relation to the Euro area, we find some evidence of bilateral volatility spillovers with Australia in the long-run and a high percentage of significant spillovers, both in the short-run and the long-run, running from the external stock markets to the domestic exchange rate market. In regard to Japan, we find evidence of inter-spillovers in the short-run and long-run and in favour of bidirectional causality in the short-run and in the long-run with Canada, as well as bidirectional causality in the long-run with the Euro area and in the short-run with Australia. With respect to Switzerland, the results suggest some inter-spillovers in the short-run, running from the external stock market to the domestic foreign exchange market. Our results indicate the existence of inter-spillovers in the short-run for the UK, running from the external exchange rates to the domestic stock market. Referring to the United States, we find some evidence of bilateral spillovers in the long-run with Canada and in the short-run with Japan, as well as some instances of unilateral spillovers in the short-run and long-run with other countries under study. Finally, it is very noticeable that we do not find any evidence of long-run volatility spillovers for Switzerland, nor for the UK running from the domestic stock market to the external foreign exchange markets in the long-run or in the short-run

All in all, our findings suggest that inter-spillovers increase substantially during the post-GFC period, providing support to the literature which documents that cross-country and cross-market linkages increase in times of growing economic and financial instability.

3.2.6. Granger-causality analysis

In this subsection we present results from the Granger (1969) approach to causality to explore the relationships between the 14 markets under study, given that the previous analysis of correlation does not necessarily imply causation in any meaningful sense of the word.

Tables 7 to 9 display the results of the pairwise intra-spillovers. As regards the entire sample (Table 7), we find evidence of bidirectional causality for Japan (both in long-run and short-run volatility), bilateral causality in long-run volatility for Switzerland and the UK, and bilateral causality in short-run volatility for Canada. The results also suggest the presence of Granger causality (at least at the 5% significance level) running one-way from the foreign market to the stock market in Australia (both in long-run and short-run volatility) and from the stock market to the foreign exchange market in the Euro area (in long-run volatility), in the UK (in short-run volatility), and in the USA (both in long-run and short-run volatility).

[Insert Table 7 here]

In the case of the results for the pre-GFC period (1 January 1990 to 8 August 2007), Table 8 suggests the existence of bidirectional causality in long-run volatility for the Euro area and Switzerland, and bilateral causality in short-run volatility for the UK. There is also evidence of unilateral causality from the stock market to the foreign exchange market for Australia (in long-run volatility) and for Canada (both in long-run and short-run volatility), as well as unilateral causality running from the foreign market to the stock market in Japan (both in long-run and short-run volatility), Switzerland (in short-run volatility) and the UK (in long-run volatility).

[Insert Table 8 here]

As can be seen in Table 9, for the post-GFC period (9 August 2007 to 31 December 2015), we find evidence of bidirectional causality for Australia and Japan (both in long-run and short-run volatility). The results also suggest the presence of Granger causality running one-way from the foreign market to the stock market in Canada and the USA (both in long-run and short-run volatility) and in the Euro area and Switzerland (in long-run volatility).

[Insert Table 9 here]

As for the inter-spillovers, Figures 4 to 9 synthetically display the main results for our Granger-causality analysis. Figures 4 to 6 illustrate the causal relationships in long-run volatility for the full sample, pre-GFC period and post-GFP, respectively. At the same time, Figures 7 to 9 illustrate the causal relationships in short-run volatility for the full sample, pre-GFC period and post-GFP, respectively. Instead of presenting the detailed results (available from the authors upon request), we provide a visualization of the complex causality network among the 14 variables in our sample[14]. The colour of the arrows indicates the significance of the causality relationships detected among the variables: black and red links correspond to the 1% and 5% level of significance respectively[15].

[Insert Figures 4 to 9 here]

Our analysis of pairwise Granger-causality relationships suggests that both the whole sample and the pre-GFC period stock markets played a dominant role in the transmission of long-run volatility, whereas during the post-GFC period the exchange-rate markets were the main long-run volatility triggers. As for the short-run volatility spillovers, the stock markets were the volatility transmitter to exchange-rate markets in all samples. Finally, the net of the Granger-causality relationships among the exchange-rate and stock markets under study becomes denser and stronger in the post-GFC period when compared to the pre-GFC period.

4. Concluding remarks

The recent GFC has underlined that the cross-market and cross-border transmission of shocks can be rapid and powerful due to the strong interlinkages in international financial markets

This paper provides a new insight into the stock–exchange rate nexus. Building upon an existing literature examining volatility transmission between financial assets that trade both within and across countries, we focus on the volatility spillovers between foreign

[14] The full results of the Granger-causality tests, not shown here to save space, are available from the authors upon request.

[15] The detail analysis of the bilateral causality relationships are not shown here to save space, but they are available from the authors upon request.

exchange and stock markets. In particular, in what we believe to be the first study to do so, we use the C-GARCH volatility model to distinguish the long-run and short-run volatility components, shedding some light on the importance of both components in the transitory volatility in these markets. Additionally, we make use of the SVAR framework (Azad *et al.*, 2015) to analyse the short-run and long-run volatility spillsovers among the exchange-rate and stock markets in major world economies and the Granger causality approach to assess whether there is evidence in favour of bidirectional or unidirectional causality between them.

The main findings of our research can be summarized as follows. (i) The estimated permanent and transitory components of the conditional variance exhibit several well-known peaks in volatilities; (ii) the long-run volatility relationships are stronger than the short-run linkages volatility with a reinforcement during the post-global financial crisis period; (iii) the presence of intra-spillovers and inter-spillovers increases substantially during the post-global financial crisis period and (iv) in all samples, the stock markets play a dominant role in the transmission of long-run and short-run volatility, except for the period after the Global Financial Crisis, where the foreign exchange markets are the main long-run volatility triggers.

In conclusion, we find unambiguous support for volatility spillovers increasing the likelihood of financial crises, which is in line with previous studies that have documented the effect of extreme market turmoil on foreign exchange and stock markets (see, for example, Hartmann *et al.* 2003; Cumperayot *et al.* 2006, Ranaldo and Söderlind 2010; or Lin 2012).

The results presented in this paper should be of value to macro-prudential and monetary policymakers, as they provide evidence on the time-varying relationship between the different components of financial volatility. Our findings may also provide useful insight into the realm of volatility forecasting, option pricing and futures hedging strategies, among others, which could be useful to portfolio managers, risk strategists and insurers but this we leave for a future study.

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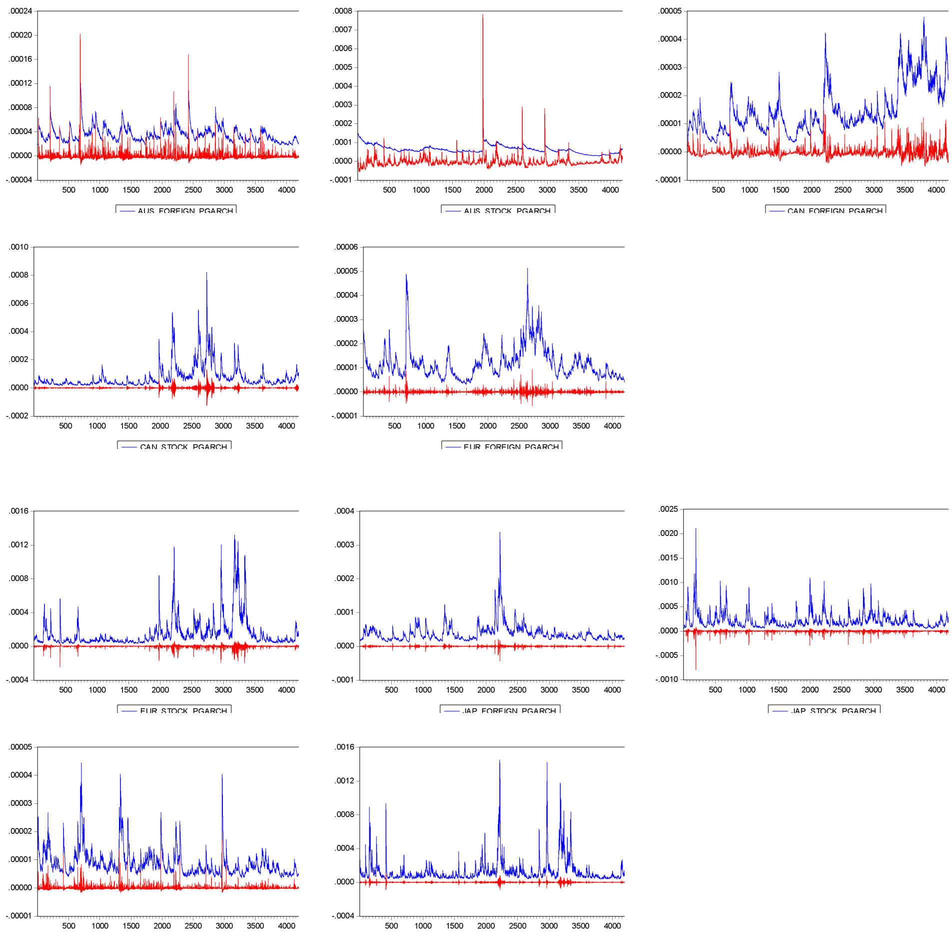
Figure 1. Permanent and Transitory volatility components, Full sample (1 January 1990 to 31 December 2015)


AUS_FOREIGN_PGARCH
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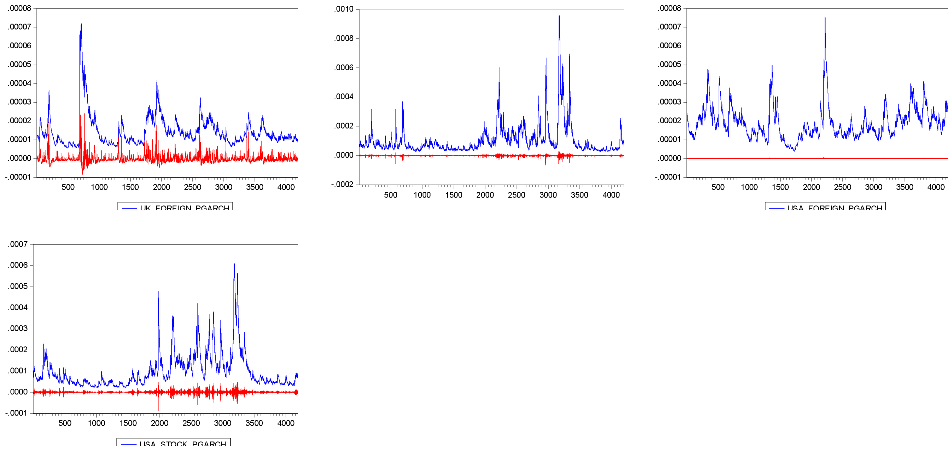
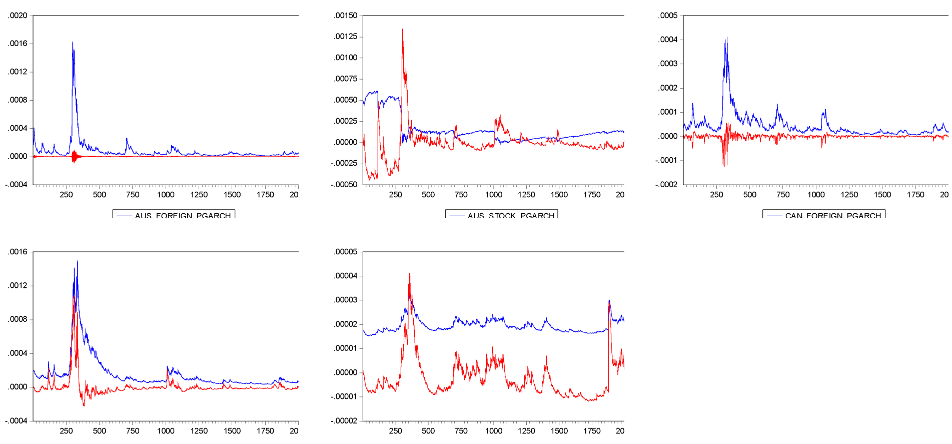


Figure 2. Permanent and Transitory volatility components, Pre-GFC period (1 January 1990 to 8 August 2007)



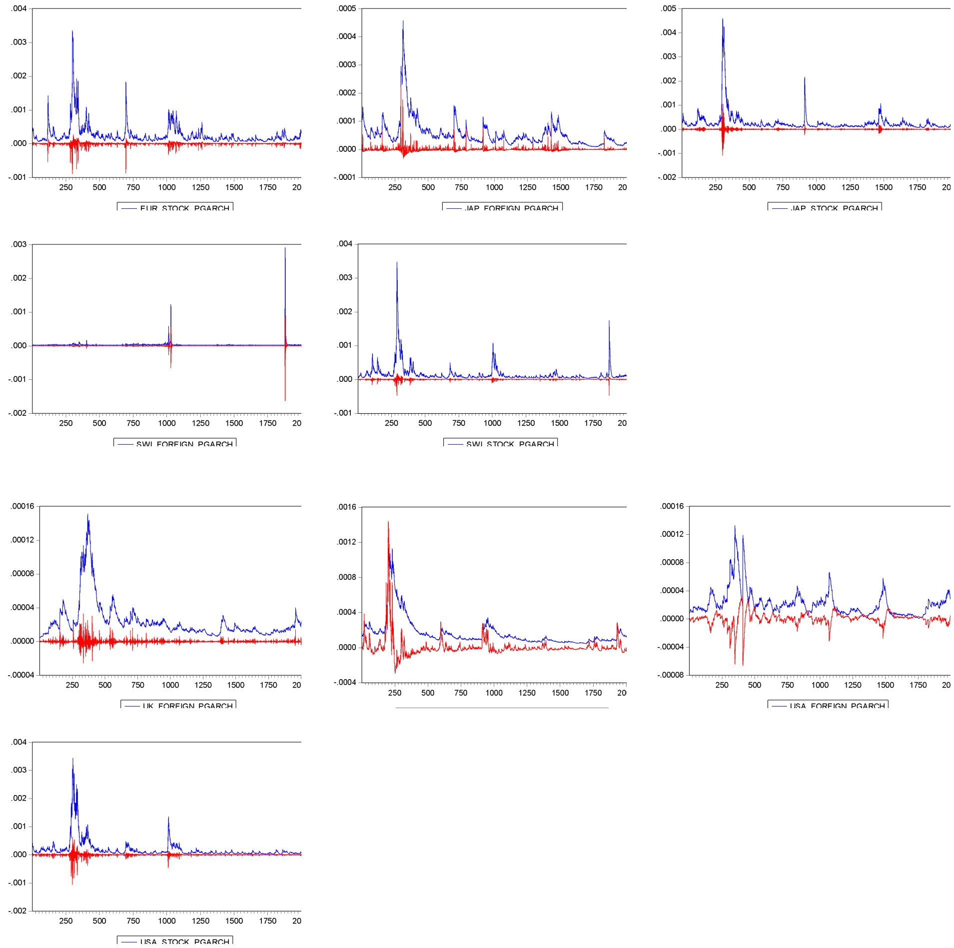


Figure 3. Permanent and Transitory volatility components, Post-GFC period (9 August 2007 to 31 December 2015)

Table 1: Intra-spillovers volatility estimations, full sample (1 January 1990 to 31 December 2015)

Country/Direction	Long-run volatility		Short-run volatility	
AOI to AUD	0.011411*	(0.00098)	0.19465*	(0.023)
AUD to AOI	0.003358	(0.00358)	0.007661	(0.002)
TSX to CAD	0.00269	(0.009487)	-0.430337***	(0.233755)
CAD to TSX	0.004555*	(0.000517)	0.002086*	(0.000144)
EUROSTOXX to EUR	0.033416	(0.069866)	0.250929	(0.389304)
EUR to EUROSTOXX	0.000269*	(0.0000631)	0.000155	(0.000396)
NIKKEI225 to JPY	0.149279*	(0.029798)	-0.605199*	(0.058416)
JPY to NIKKEI225	0.001494*	(0.000318)	0.011049*	(0.002389)
SMI to CHF	-0.097682**	(0.033759)	0.005672**	(0.002544)
CHF to SMI	0.001042***	(0.000555)	0.040986**	(0.01797)
FTSE100 to GBP	-0.024905**	(0.011627)	-0.207482***	(0.1254)
GBP to FTSE100	0.001726*	(0.000246)	0.001981*	(0.000382)
SP500 to USD	-0.0419	(0.0389)	-0.076563	(0.171378)
USD to SP500	0.000751*	(0.00011)	0.00185*	(0.000332)

Notes:

AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

The results are based on equations (4a)-(4b) and (5a)-(5b) for the long-run and short-run volatility, respectively.

*,**, *** indicate that the coefficients are significant at 1%, 5% and 10%, respectively.

In parentheses are standard errors of estimated coefficients.

Table 2: Intra-spillovers volatility estimations, pre-GFC period (1 January 1990 to 8 August 2007)

Country/Direction	Long-run volatility		Short-run volatility	
AOI to AUD	0.001765	(0.002237)	0.054219*	(0.022653)
AUD to AOI	0.003953**	(0.00201)	0.00298	(0.003231)
TSX to CAD	-0.025792	(0.027608)	-0.05101***	(0.028362)
CAD to TSX	0.000274	(0.00019)	-0.000404	(0.001445)
EUROSTOXX to EUR	-0.069835	(0.074856)	-0.67392**	(0.357294)
EUR to EUROSTOXX	0.000151**	(7.68E-05)	-0.001616*	(0.000493)
NIKKEI225 to JPY	0.03584	(0.027455)	0.711716*	(0.180158)
JPY to NIKKEI225	0.000694	(0.000469)	-0.000362	(0.000834)
SMI to CHF	-0.440568*	(0.131721)	0.233516*	(0.078509)
CHF to SMI	0.000502*	(0.000123)	-0.001095	(0.001325)
FTSE100 to GBP	-0.061185**	(0.032156)	-0.027685	(0.021126)
GBP to FTSE100	0.000302**	(0.00015)	-0.004298	(0.005869)
SP500 to USD	-0.019506	(0.019369)	-1.362785	(1.641133)
USD to SP500	0.000318	(0.000228)	1.88E-05	(5.83E-05)

Notes:

AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss

Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

The results are based on equations (4a)-(4b) and (5a)-(5b) for the long-run and short-run volatility, respectively.

*,**, *** indicate that the coefficients are significant at 1%, 5% and 10%, respectively.

In parentheses are standard errors of estimated coefficients.

Table 3: Intra-spillovers volatility estimations, post-GFC period (9 August 2007 to 31 December 2015)

Country/Direction	Long-run volatility		Short-run volatility	
AOI to AUD	-0.007522*	(0.00139)	0.689879*	(0.07419)
AUD to AOI	0.008786*	(0.003747)	0.000566*	(0.000187)
TSX to CAD	8.02E-05	(0.021139)	0.077954	(0.062386)
CAD to TSX	0.01469*	(0.001715)	-0.010428*	(0.001447)
EUROSTOXX to EUR	0.958903	(0.67116)	-0.105437	(0.157834)
EUR to EUROSTOXX	7.54E-05*	(3.14E-05)	0.000527	(0.000427)
NIKKEI225 to JPY	0.335102*	(0.066706)	-0.311701*	(0.048538)
JPY to NIKKEI225	0.003582*	(0.000757)	0.016446*	(0.002885)
SMI to CHF	-0.019401	(0.013799)	-0.018094***	(0.011309)
CHF to SMI	0.014233**	(0.00628)	-0.025488	(0.034049)
FTSE100 to GBP	-0.001776	(0.019282)	0.397525	(0.306084)
GBP to FTSE100	0.000507	(0.000342)	-0.000568	(0.000476)
SP500 to USD	0.098071	(0.102325)	-0.044264	(0.129094)
USD to SP500	0.001267*	(0.000237)	0.004994*	(0.00105)

Notes:

AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss

Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

The results are based on equations (4a)-(4b) and (5a)-(5b) for the long-run and short-run volatility, respectively.

*,**, *** indicate that the coefficients are significant at 1%, 5% and 10%, respectively.

In parentheses are standard errors of estimated coefficients.

Table 4: Inter-spillovers volatility estimations, full sample (1 January 1990 to 31 December 2015)

Country/Direction	Long-run volatility		Short-run volatility		Country/Direction	Long-run volatility	
AOI					**TSX**		
USD	-1.84E-03	(7.37E-03)	-0.084547	(2.12E-01)	AUD	0.046948*	(0.003654)
CAD	-6.05E-03	(3.88E-03)	1.36E+00*	(2.11E-01)	USD	-0.005978	(0.021104)
EUR	9.50E-04	(9.40E-03)	-2.46E-01	(3.37E-01)	EUR	0.036944	(0.027894)
JPY	-3.35E-04	(2.52E-03)	-5.87E-03	(5.45E-02)	JPY	-0.007192	(0.007367)
CHF	1.65E-03	(3.19E-03)	4.76E-03	(1.00E-02)	CHF	-0.001801	(0.009161)
GBP	-0.004157	(6.32E-03)	1.37E-01	(1.01E-01)	GBP	-0.013002	(0.017782)
AUD					**CAD**		
SP500	2.14E-02*	(2.55E-03)	-0.030503*	(5.67E-03)	TSX	0.00417*	(0.001481)
TSX	-5.94E-03*	(3.05E-03)	2.38E-02*	(3.30E-03)	SP500	5.98E-03*	(6.18E-04)
EUROSTOXX	2.27E-05	(2.06E-03)	2.39E-02*	(5.71E-03)	EUROSTOXX	-0.000593	(0.000543)
NIKKEI225	-2.85E-03*	(9.44E-04)	1.36E-02**	(5.44E-03)	NIKKEI225	0.000329	(0.000227)
SMI	3.81E-05	(1.84E-03)	1.20E-02	(1.01E-02)	SMI	-0.000196	(0.000493)
FTSE100	-1.92E-02*	(4.61E-03)	-6.04E-03*	(2.81E-03)	FTSE100	-0.004504*	(0.001231)
EUROSTOXX					**NIKKEI225 to**		
AUD	0.08729*	(0.013683)	-0.241412*	(0.033287)	AUD	0.319193*	(0.02174)
CAD	-0.138269*	(0.035872)	0.891683*	(0.270681)	CAD	-0.330474*	(0.049455
USD	0.084551	(0.076308)	-0.244636	(0.268323)	EUR	-0.299039**	(0.13453)
JPY	-0.016158	(0.026139)	-0.025435	(0.069671)	USD	0.124065	(0.104724
CHF	-0.015805	(0.032972)	-0.002166	(0.012773)	CHF	0.022215	(0.045312
GBP	0.02043	(0.064799)	-0.228894***	(0.128138)	GBP	0.082158	(0.088075
EUR					**JPY**		
AOI	-0.000769***	(0.000452)	-5.66E-06	(0.000254)	AOI	0.002192	(0.002303)
TSX	0.000951*	(0.000281)	0.000617**	(0.000262)	TSX	0.004126**	(0.001385)
SP500	3.09E-05	(2.02E-04)	-0.000734***	(0.000453)	EUROSTOXX	-0.001748**	(0.000899)
NIKKEI225	0.000112	(7.40E-05)	0.000317	(0.000425)	SP500	0.001091	(0.001016)
SMI	0.000149	(0.000159)	0.002546*	(0.000803)	SMI	0.005094*	(0.000818)
FTSE100	-0.000577	(0.0004)	0.000121	(0.000224)	FTSE110	-0.005366	0.002031

Table 5: Inter-spillovers volatility estimations, full sample (1 January 1990 to 31 December 2015) (cont.)

Country/Direction	Long-run volatility		Short-run volatility		Country/Direction	Long-run volatility	
SMI					**FTSE100**		
AUD	0.12635*	(0.015028)	0.003109	(0.00316)	AUD	0.033051*	(0.003406)
CAD	-0.191037*	(0.037632)	-0.000441	(0.001843)	CAD	-0.0481*	(0.009389)
EUR	-0.103629	(0.101914)	0.003247**	(0.001247)	EUR	0.009049	(0.024579)
JPY	-0.000155	(0.02761)	-0.000383	(0.000521)	JPY	-0.007757	(0.006546)
USD	0.157724**	(0.080474)	0.001675	(0.001393)	CHF	-0.001132	(0.008262)
GBP	-0.010578	(0.067428)	-0.005762**	(0.00279)	USD	0.021581	(0.019188)
CHF					**GBP**		
AOI	0.086922*	(0.006829)	0.004493	(0.005885)	AOI	0.000753	(0.00079)
TSX	-0.297168*	(0.058263)	-0.005633	(0.006075)	TSX	0.001183*	(0.000467)
EUROSTOXX	0.041728	(0.089931)	-0.015491	(0.010293)	EUROSTOXX	-0.000374	(0.000302)
NIKKEI225	-0.05754*	(0.014549)	0.000872	(0.009835)	NIKKEI225	0.000596*	(0.000126)
SP500	0.003225	(0.056156)	-0.001536	(0.010464)	SMI	0.000196	(0.000272)
FTSE100	-0.043009***	(0.026839)	0.005381	(0.005184)	SP500	-0.000668**	(0.000345)
SP500							
AUD	0.151454*	(0.01012)	-0.363247*	(0.021841)			
CAD	-0.115766*	(0.024093)	-0.114631	(0.180014)			
EUR	0.090468	(0.06377)	0.604088**	(0.287605)			
JPY	-0.010655	(0.01699)	0.142639**	(0.046596)			
CHF	-0.004547	(0.021424)	-0.004246	(0.008548)			
GBP	-0.015954	(0.04169)	-0.195092*	(0.086021)			
USD							
AOI	-0.000267	(0.000681)	3.87E-04**	(2.03E-04)			
TSX	0.001059*	(0.000402)	-0.000817*	(0.00021)			
EUROSTOXX	-0.000698*	(0.000264)	-0.001189*	(0.000356)			
NIKKEI225	5.13E-05	(0.00011)	-3.31E-06	(3.40E-04)			
SMI	0.000976*	(0.000239)	-0.001359**	(0.000643)			
FTSE100	0.000161	(0.000603)	-0.000205	(0.00018)			

Notes: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates. The results are based on equations (6a)-(6b) and (7a)-(7b) for the long-run and short-run volatility, respectively. *,**, *** indicate that the coefficients are significant at 1%, 5% and 10%, respectively. In parentheses are standard errors of estimated coefficients.

Table 6: Inter-spillovers volatility estimations, pre-GFC period (1 January 1990-8 August 2007)

Country/Direction	Long-run volatility		Short-run volatility		Country/Direction	Long-run volatility	
AOI					**TSX**		
USD	-0.003565	(0.004386)	3.487047	(6.436488)	AUD	-0.015486	(0.023322
CAD	-0.008162**	(0.004284)	0.158199	(0.110838)	USD	-0.082662**	(0.036995
EUR	-0.00617	(0.005634)	0.064522	(0.294976)	EUR	0.148261*	(0.052584
JPY	0.002465***	(0.001387)	-0.086797	(0.093205)	JPY	0.02409**	(0.011937
CHF	-0.010021	(0.007249)	1.165903*	(0.231752)	CHF	-0.09741***	(0.059093
GBP	0.005615	(0.004709)	-0.053541	(0.065753)	GBP	-0.027402	(0.038918
AUD					**CAD**		
SP500	-0.001014	(0.001088)	-0.016801	(0.017636)	AOI	-0.002455*	(0.000915
TSX	0.001059	(0.000688)	0.005727	(0.011652)	SP500	-0.000793**	(0.000418
EUROSTOXX	-0.001738**	(0.00081)	-0.016642***	(0.008348)	EUROSTOXX	-0.000158	(0.000312
NIKKEI225	0.001103*	(0.00028)	-0.002738	(0.00433)	NIKKEI225	8.56E-05	(0.000107
SMI	0.001187**	(0.000602)	-0.007816	(0.01195)	SMI	0.000455**	(0.000231
FTSE100	0.002204**	(0.001124)	0.019936	(0.031814)	FTSE100	0.000427	(0.000425
EUROSTOXX					**NIKKEI225**		
AUD	0.065301	(0.050335)	-0.02393	(0.029183)	AUD	-0.096554	(0.070083
CAD	-0.118712***	(0.069516)	-0.155075	(0.136781)	CAD	-0.172372***	(0.096748
USD	0.057388	(0.077052)	-8.99583	(8.0079)	EUR	-0.068128	(0.137055
JPY	0.015805	(0.023632)	0.437084*	(0.115927)	USD	0.027646	(0.107413
CHF	-0.5391*	(0.126339)	-1.003032*	(0.292977)	CHF	0.05867	(0.178464
GBP	0.070509	(0.083139)	-0.090894	(0.081646)	GBP	0.068941	(0.114385
EUR					**JPY**		
AOI	-0.000972	(0.000723)	0.000537**	(0.000245)	AOI	0.001126	(0.003985
TSX	0.00093*	(0.000239)	0.000398	(0.000869)	TSX	0.006382*	(0.001291
SP500	-0.000425	(0.00036)	-7.43E-05	(0.001316)	EUROSTOXX	-0.006722*	(0.001478
NIKKEI225	0.000304*	(9.27E-05)	-0.000375	(0.000323)	SP500	-0.001322	(0.001972
SMI	0.000162	(0.000202)	-0.000303	(0.000893)	SMI	0.010104*	(0.001124
FTSE100	0.000511	(0.000369)	-0.001998	(0.002372)	FTSE100	0.001156	(0.002018

Table 7: Inter-spillovers volatility estimations, pre-GFC period (1 January 1990 to 8 August 2007) (cont.)

Country/Direction	Long-run volatility		Short-run volatility		Country/Direction	Long-run volatility	
SMI					**FTSE100**		
AUD	0.0194	(0.033535)	-0.00917	(0.012443)	AUD	-0.258603	(0.19116)
CAD	-0.086465	(0.06564)	-0.714396*	(0.135987)	CAD	-1.126237	(2.073805)
EUR	-0.164893	(0.122878)	0.096968	(0.112693)	EUR	0.986944	(1.726895)
JPY	0.033759	(0.028948)	0.034252**	(0.01651)	JPY	0.210563	(0.253221)
USD	0.054767	(0.095698)	0.087052	(0.07515)	CHF	-1.70309*	(0.522065)
GBP	0.098716	(0.087041)	0.02611	(0.036491)	USD	3.617837*	(1.166061)
SMI					**GBP**		
AOI	3.83E-05	(0.000482)	0.001158**	(0.000724)	AOI	-0.000128	(0.001116)
TSX	-0.000129	(0.000198)	0.001408**	(0.000834)	TSX	0.000317	(0.000466)
EUROSTOXX	-0.000187	(0.000185)	0.00129	(0.001346)	EUROSTOXX	0.000496	(0.000432)
NIKKEI225	0.000207*	(6.47E-05)	0.000424	(0.001164)	NIKKEI225	0.000418*	(0.000151)
SP500	-0.000215	(0.00022)	-0.009597*	(0.001917)	SMI	7.56E-05	(0.000335)
FTSE100	-4.71E-05	(0.000314)	0.001177**	(0.000549)	SP500	-0.000745	(0.000513)
SP500							
AUD	0.008738	(0.014068)	-0.023353	(0.026971)			
CAD	-0.010641	(0.027583)	-0.161152	(0.293285)			
EUR	0.047266	(0.053787)	-0.046843	(0.244246)			
JPY	0.016433	(0.012073)	0.008458	(0.035793)			
CHF	-0.395091**	(0.171459)	0.046201	(0.073015)			
GBP	0.000788	(0.036581)	-0.031811	(0.079081)			
USD							
AOI	-0.003052**	(0.001006)	0.000616*	(0.000242)			
TSX	0.000743***	(0.000415)	-0.001354*	(0.000284)			
EUROSTOXX	-0.001569*	(0.000386)	0.000878**	(0.000453)			
NIKKEI225	0.000205	(0.000135)	2.24E-05	(0.000396)			
SMI	0.00228*	(0.000305)	0.000411	(0.000678)			
FTSE100	0.000716	(0.000655)	-0.000458*	(0.000188)			

Notes: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates. The results are based on equations (6a)-(6b) and (7a)-(7b) for the long-run and short-run volatility, respectively. *,**, *** indicate that the coefficients are significant at 1%, 5% and 10%, respectively. In parentheses are standard errors of estimated coefficients.

Table 8: Inter-spillovers volatility estimations, post-GFC period (9 August 2007 to 31 December 2015)

Country/Direction	Long-run volatility		Short-run volatility		Country/Direction	Long-run volatility	
AOI					**TSX**		
USD	-0.009102	(0.018944)	0.036573	(0.079856)	AUD	0.070152*	(0.007389)
CAD	0.050081*	(0.009718)	-0.447322*	(0.066861)	USD	0.058577	(0.044284)
EUR	-0.223082**	(0.1157)	0.174137**	(0.094298)	EUR	-0.180589	(0.245916)
JPY	0.013162	(0.009666)	0.107029	(0.071779)	JPY	-0.049219**	(0.022386)
CHF	0.001125	(0.002016)	0.00258	(0.01379)	CHF	0.001977	(0.004655)
GBP	-0.001523	(0.01879)	0.662306*	(0.225892)	GBP	0.168336*	(0.048744)
AUD					**CAD**		
SP500	0.011516**	(0.005878)	0.002323*	(0.000618)	AOI	0.002282**	(0.001341
TSX	-0.005519	(0.005969)	-0.001755*	(0.000415)	SP500	0.009403*	(0.001529
EUROSTOXX	-0.01173*	(0.004196)	-0.002497*	(0.000641)	EUROSTOXX	-0.003801*	(0.001128
NIKKEI225	-0.010794*	(0.003089)	-0.002504*	(0.000677)	NIKKEI225	0.001378**	(0.000668
SMI	0.03301*	(0.003197)	0.001759	(0.001404)	SMI	0.000441	(0.000887
FTSE100	-0.000433	(0.005016)	0.000593**	(0.000307)	FTSE100	-0.001909	(0.001361
EUROSTOXX					**NIKKEI225**		
AUD	0.237982*	(0.029225)	0.414915**	(0.141043)	AUD	0.483953*	(0.033282)
CAD	-0.383899*	(0.085176)	0.124438	(0.126613)	CAD	-0.625647*	(0.090017)
USD	0.147946	(0.163948)	-0.045287	(0.150787)	EUR	-2.009149**	(0.976174)
JPY	-0.152204**	(0.084335)	0.2627***	(0.143266)	USD	0.218328	(0.173681)
CHF	0.001704	(0.017553)	0.024402	(0.026151)	CHF	0.011639	(0.018545)
GBP	0.379698**	(0.163507)	-0.757213***	(0.42841)	GBP	0.374687**	(0.17226)
EUR					**JPY**		
AOI	-0.000133***	(7.65E-05)	-1.75E-05	(0.000198)	AOI	0.000327	(0.001543)
TSX	0.000126	(9.65E-05)	0.000839**	(0.000298)	TSX	0.006084*	(0.002083)
SP500	-4.65E-05	(8.24E-05)	-0.000581	(0.000441)	EUROSTOXX	-0.003681*	(0.00129)
NIKKEI225	1.95E-05	(3.58E-05)	-0.0002	(0.000353)	SP500	0.000128	(0.001752)
SMI	0.00016*	(4.64E-05)	-0.002221**	(0.001003)	SMI	0.008071*	(0.000993)
FTSE100	5.46E-05	(7.34E-05)	-0.000248	(0.000219)	FTSE100	-0.001328	(0.001565)

Table 9: Inter-spillovers volatility estimations, post-GFC period (9 August 2007 to 31 December 2015) (cont.)

Country/Direction	Long-run volatility		Short-run volatility		Country/Direction	Long-run volatility	
SMI					**FTSE100**		
AUD	-0.014465	(0.022548)	0.189186*	(0.060799)	AUD	-0.000331	(0.006064)
CAD	0.062416	(0.069854)	-0.020606	(0.052559)	CAD	-0.025824	(0.019467)
EUR	-0.182042	(0.749343)	0.001364	(0.071107)	EUR	-0.266079	(0.217283)
JPY	-0.063518	(0.069109)	0.20332*	(0.058614)	JOY	0.022401	(0.019654)
USD	-0.068684	(0.134959)	-0.066231	(0.0648)	CHF	7.33E-05	(0.004012)
GBP	0.086497	(0.133061)	0.416112**	(0.184651)	USD	0.018594	(0.037791)
CHF					**GBP**		
AOI	-0.005957	(0.013542)	-0.00306	(0.006595)	AOI	-0.000125	(0.000442)
TSX	-0.007665	(0.016438)	-0.000443	(0.010559)	TSX	0.004238*	(0.000816)
EUROSTOXX	0.018021	(0.011488)	0.0318**	(0.016306)	EUROSTOXX	-0.000258	(0.000374)
NIKKEI225	-0.004816	(0.006696)	-0.002815	(0.012571)	NIKKEI225	0.000753*	(0.00022)
SP500	-0.008256	(0.015564)	-0.009298	(0.015701)	SMI	0.000567**	(0.000289)
FTSE100	-0.001639	(0.013833)	0.001215	(0.00781)	SP500	-0.001605*	(0.000521)
SP500							
AUD	0.349377*	(0.027937)	0.11587	(0.128424)			
CAD	-0.404882*	(0.076723)	-0.026129	(0.110812)			
EUR	0.217479	(0.818511)	-0.148381	(0.149934)			
JPY	-0.113735	(0.075354)	-0.372875**	(0.123678)			
CHF	0.008002	(0.015705)	0.012172	(0.023708)			
GBP	0.516697*	(0.145864)	-0.521158	(0.391423)			
USD							
AOI	-4.29E-05	(0.000581)	0.000454	(0.000482)			
TSX	0.002385*	(0.00089)	-0.003*	(0.000791)			
EUROSTOXX	-0.001109**	(0.000491)	-0.005136*	(0.001192)			
NIKKEI225	0.000343	(0.000287)	0.003127*	(0.000919)			
SMI	0.000731**	(0.000379)	0.009771*	(0.002612)			
FTSE100	-0.000248	(0.000593)	0.001029**	(0.000573)			

Notes: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US Dollar effective exchange rates. The results are based on equations (6a)-(6b) and (7a)-(7b) for the long-run and short-run volatility, respectively. *,**, *** indicate that the coefficients are significant at 1%, 5% and 10%, respectively. In parentheses are standard errors of estimated coefficients.

Table 10: Intra-spillovers Granger causality, full sample (1 January 1990 to 31 December 2015)

Null Hypothesis	Long-run volatility		Short-run volatility	
	F-statistic	p-value	F-statistic	p-value
AOI does not Granger cause AUD	0.15227	0.8588	2.6221	0.0727
AUD does not Granger cause AOI	64.9456	1.00E-28	176.313	3.00E-75
TSX does not Granger cause CAD	59.4183	3.00E-26	110.976	4.00E-48
CAD does not Granger cause TSX	1.01183	0.3636	1.91268	1.48E-01
EUROSTOXX does not Granger cause EUR	9.233	0.0001	1.38918	0.2494
EUR does not Granger cause EUROSTOXX	0.25686	0.7735	0.68887	0.5022
NIKKEI225 does not Granger cause JPY	25.5034	9.00E-12	13.0576	2.00E-06
JPY does not Granger cause NIKKEI225	29.5599	2.00E-13	55.2204	2.00E-24
SMI does not Granger cause CHF	3.60548	2.72E-02	3.05451	0.0472
CHF does not Granger cause SMI	44.7976	5.00E-20	39.857	6.00E-18
FTSE100 does not Granger cause GBP	28.7695	4.00E-13	21.7695	4.00E-10
GBP does not Granger cause FTSE100	3.56451	0.0284	0.95063	0.3866
SP500 does not Granger cause USD	34.0228	2.00E-15	18.2244	1.00E-08
USD does not Granger cause SP500	0.93759	0.3916	0.15594	0.8556

Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, Canadian dollar, British pound and US Dollar effective exchange rates

Table 11. Intra-spillovers Granger causality, pre-GFC period (1 January 1990 to 8 August 2007)

Null Hypothesis	Long-run volatility		Short-run volatility	
	F-statistic	p-value	F-statistic	p-value
AOI does not Granger cause AUD	2.7869785	0.06171481	0.99634	0.3693
AUD does not Granger cause AOI	0.84982454	0.42755942	1.62655	0.1967
TSX does not Granger cause CAD	3.9058	0.0202	3.63886	0.0264
CAD does not Granger cause TSX	1.284	0.277	1.84162	0.1587
EUROSTOXX does not Granger cause EUR	4.26743	0.0141	4.53323	0.0108
EUR does not Granger cause EUROSTOXX	3.35427	0.035	2.56563	0.077
NIKKEI225 does not Granger cause JPY	2.6639	0.0698	2.53391	0.0795
JPY does not Granger cause NIKKEI225	17.6385	2.00E-08	16.7825	5.00E-08
SMI does not Granger cause CHF	7.17147	0.0008	2.32783	0.0976
CHF does not Granger cause SMI	15.237	3.00E-07	5.65037	0.0035
FTSE100 does not Granger cause GBP	2.44804	0.0866	5.38613	0.0046
GBP does not Granger cause FTSE100	11.0965	2.00E-05	9.28863	9.00E-05
SP500 does not Granger cause USD	2.10125	0.1224	2.14169	0.1176
USD does not Granger cause SP500	0.91601	0.4002	0.36373	0.6951

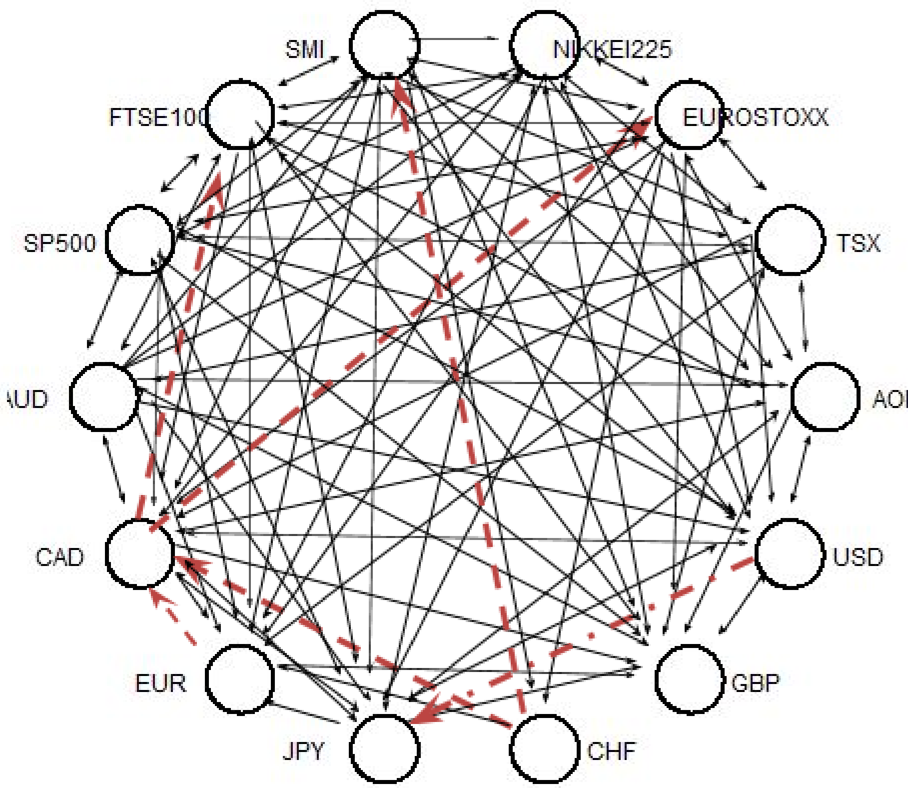
Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates

Table 12: Intra-spillovers Granger causality, post-GFC period (9 August 2007 to 31 December 2015)

Null Hypothesis	Long-run volatility		Short-run volatility	
	F-statistic	p-value	F-statistic	p-value
AOI does not Granger cause AUD	3.01751	0.0491	4.89271	0.0076
AUD does not Granger cause AOI	19.1346	6.00E-09	49.841	7.00E-22
TSX does not Granger cause CAD	2.00406	0.135	2.12089	0.1202
CAD does not Granger cause TSX	41.0816	3.00E-18	29.5162	2.00E-13
EUROSTOXX does not Granger cause EUR	2.43539	0.0878	1.56494	0.2093
EUR does not Granger cause EUROSTOXX	5.22806	0.0054	2.01706	0.1333
NIKKEI225 does not Granger cause JPY	14.1079	8.00E-07	53.7623	2.00E-23
JPY does not Granger cause NIKKEI225	20.427	2.00E-09	14.1077	8.00E-07
SMI does not Granger cause CHF	0.72843	0.4828	1.27592	0.2794
CHF does not Granger cause SMI	4.6346	0.0098	1.27875	0.2786
FTSE100 does not Granger cause GBP	1.21202	0.2978	1.15406	0.3156
GBP does not Granger cause FTSE100	1.29751	0.2734	1.54178	0.2143
SP500 does not Granger cause USD	0.4156	0.66	0.46463	0.6284
USD does not Granger cause SP500	20.605	1.00E-09	11.6658	9.00E-06

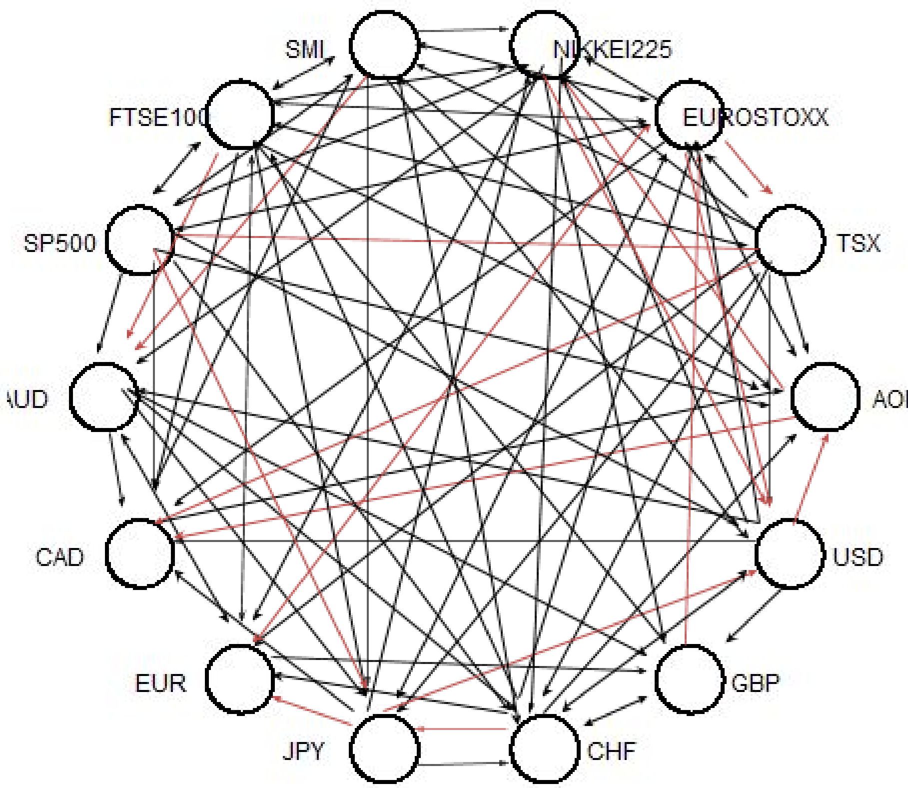
Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US Dollar effective exchange rates

Figure 4: Causal relationships in long-run volatility, full sample (1 January 1990 to 31 December 2015)



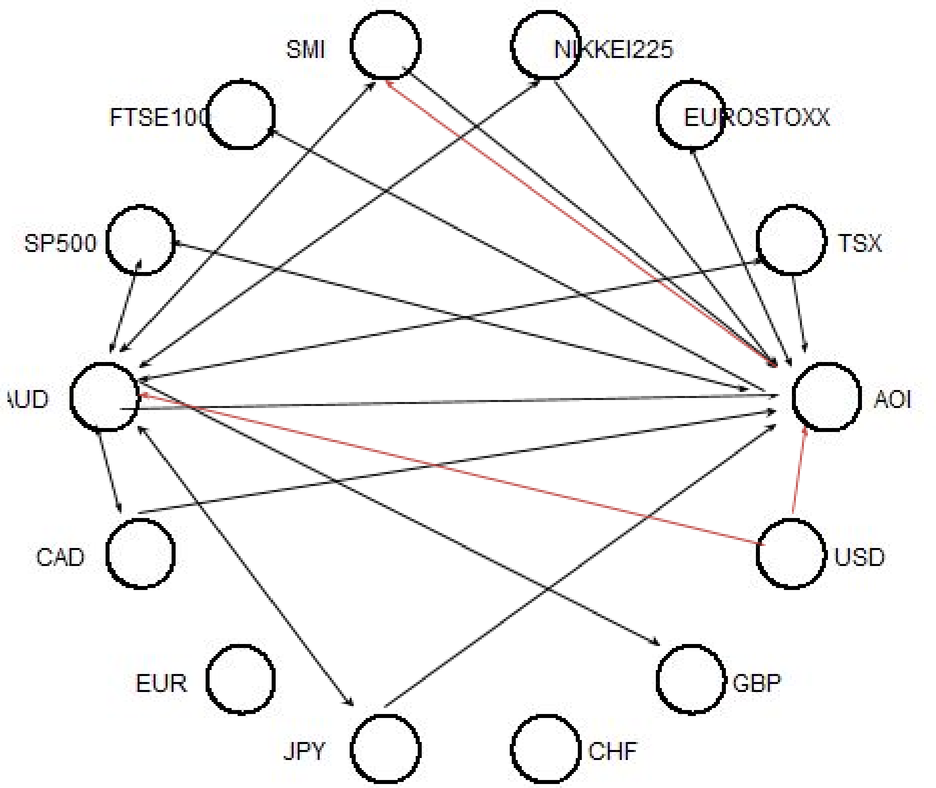
Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

Figure 5: Causal relationships in long-run volatility, pre-GFC period (1 January 1990 to 8 August 2007)



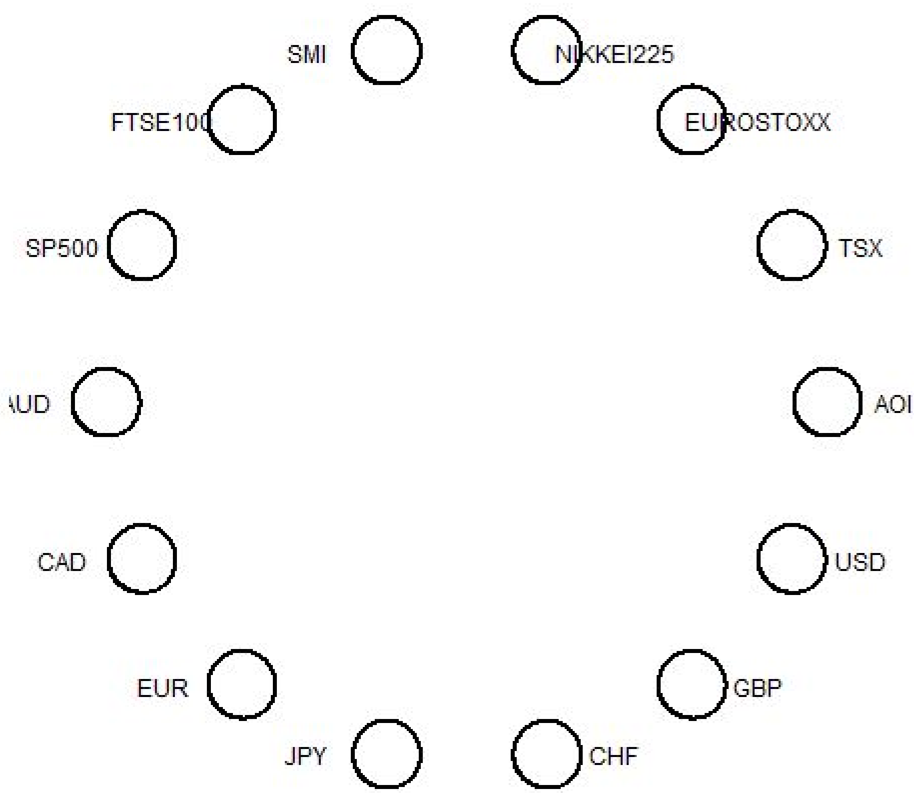
Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

Figure 6: Causal relationships in long-run volatility, post-GFC period (9 August 2007 to 31 December 2015)



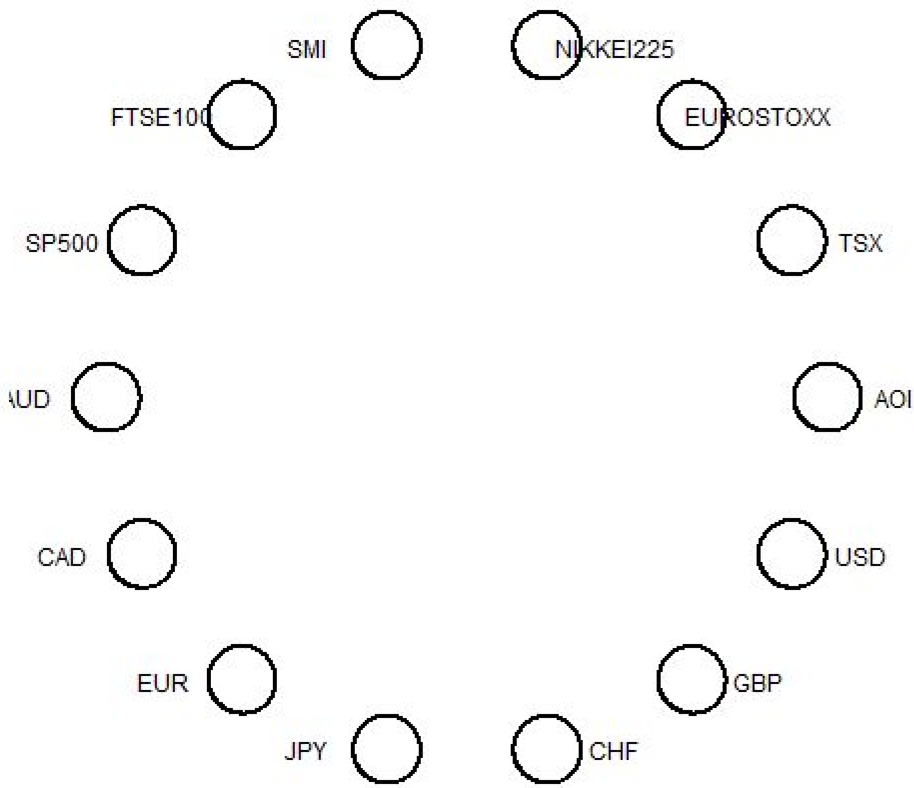
Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

Figure 7: Causal relationships in short-run volatility, full sample (1 January 1990 to 31 December 2015)



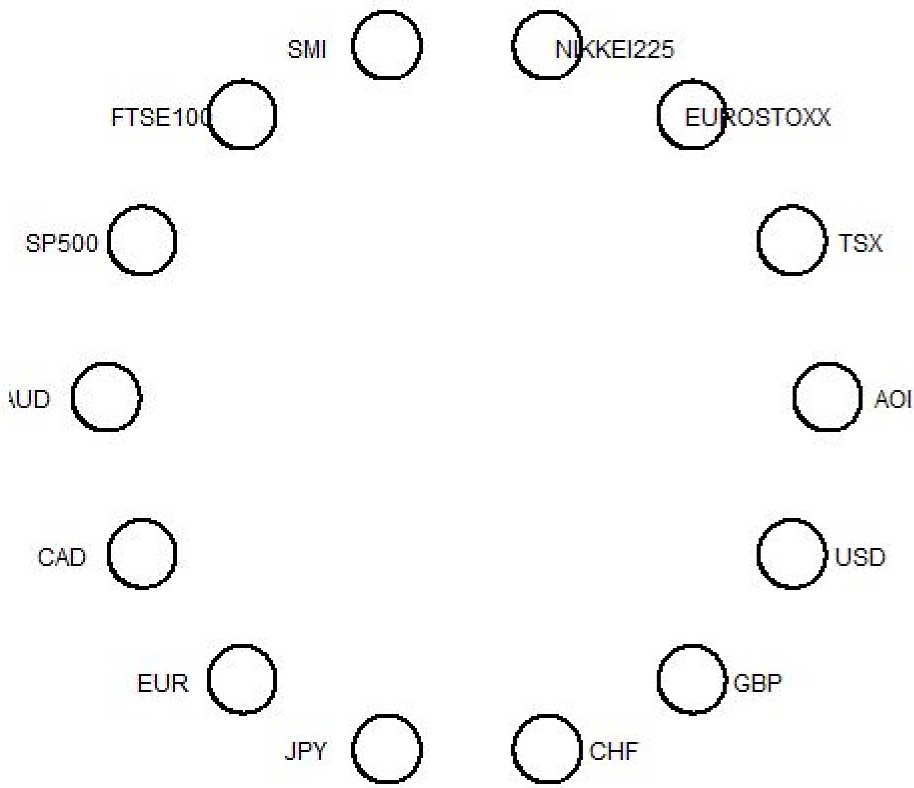
Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

Figure 8: Causal relationships in short-run volatility, pre-GFC period (1 January 1990 to 8 August 2007)



Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.

Figure 9: Causal relationships in short-run volatility, post-GFC period (9 August 2007 to 31 December 2015)



Note: AOI, TSX, EUROSTOXX, NIKKEI225, SMI, FTSE100, SP500, AUD, CAD, EUR, JPY, CHF, GBP and USD stand for Australian All Ordinaries Index, Toronto Stock Exchange index, Eurostoxx 50 Index, Nikkei 225 index, Swiss Market Index, Financial Times Stock Exchange 100 Index, Standard & Poor's 500 composite index, Australian dollar, Canadian dollar, Euro, Japanese yen, Swiss franc, British pound and US dollar effective exchange rates.