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Financial crises and stock market volatility transmission: evidence from Australia, Singapore, the UK, and the US

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Keywords

Financial, crises, stock, market, volatility, transmission, evidence, from, Australia, Singapore

Disciplines

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FINANCIAL CRISES AND STOCK MARKET VOLATILITY TRANSMISSION: EVIDENCE FROM AUSTRALIA, SINGAPORE, THE UK, AND THE US

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Abstract

With the globalization of international trade and finance, the interaction between international financial markets has increased markedly. Therefore, this paper examines the nature of interaction between stock market returns and their volatility, with a particular focus on the global financial crises in 1998 and 2008 for Australia, Singapore, the UK, and the US. This study applies multivariate generalised autoregressive conditional heteroskedasticity (MGARCH) model with dummy variables for weekly data spanning from January 1992 to June 2009. Based on the results obtained from the mean return equations, we could not find any significant impact on returns arising from 1998 and 2008 global financial crises within these four markets. However, the recent crisis in 2008 increased the stock return volatilities across all of the four markets. More generally, other results show that the US stock market is the most influential market towards volatilities of smaller economies. Estimation results provide evidence of both own and cross ARCH and GARCH effects among all four markets, suggesting the existence of significant volatility and cross volatility spillovers across all four markets. The existence of higher degree time-varying co-volatility among these four markets suggests that investors will be highly unlikely to benefit from a reduction of risk if they diversify their financial portfolio with stocks within four countries only.

JEL: G01, G15, F36

Keywords: Multivariate GARCH, Stock market returns, Financial crisis, Australia.

I Introduction

The interaction between financial markets has increased with the integration of national economies through international trade and finance. The understanding of cross-market linkages and interaction is useful for pricing of securities, developing trading strategies, hedging strategies, and regulatory strategies within, and across the markets (Brailsford 1996, Theodossiou *et al.* 1997). Therefore, studying financial market integration has become a major concern among market participants, regulators, and research scholars alike (Kim & Rogers 1995, Chan *et al.* 1997, Kanas 1998, Chou *et al.* 1999, Reyes 2001, Hassan & Malik 2007, In 2007, Li 2007, Harju & Hussain 2008). Notably, the significance of this area of analysis has increased in recent years since the emergence of global financial crises.

In this regard, empirical studies typically found that financial crises increase the volatility of stock markets (Schwert 1989). In addition, other studies have evaluated the volatility transmission across different stock markets during financial crises (Theodossiou *et al.* 1997, Ellis & Lewis 2001, Polasek & Ren 2001, Caporale *et al.* 2006, Tsouma 2007). For instance, the nature of this volatility transmission has been found to be different from one financial market to the other market in terms of size and shocks due to financial crises (Caporale *et al.* 2006, Tsouma 2007). In addition, Ellis & Lewis (2001) identified that financial market volatility in Australia and New Zealand was greater in late 1998 than 1997-1998, when the main events of Asian financial crisis occurred. The literature has shown that there are variations of impact-timeline from market to market. According to the Bank for International Settlements (1999), the Asian financial crisis started in mid-1997 with the financial collapse of the Thai-baht, mainly spread within Asia until mid-1998, and subsequently spread to Russia, and other countries. The more recent crisis started in early 2007 in the US with the collapse of the subprime mortgage market (Bordo 2008). Since then following several key incidents, it became worse in September 2008 with the fallout from the Lehman bankruptcy and then turned the liquidity crisis into a full-fledged global credit crunch and stock market crash. Furthermore, Bordo pointed out that stock market crashes and banking panics have resulted in many countries within a few months of the original event. In this regard, it is difficult to justify the specific time period, which cause the economic activities of several countries due to a specific crisis.

This study extends the existing literature analysing systematic pattern of returns and volatility spillovers due to two major financial crises: during the 1997-1998 and 2008-2009 periods. In this regard, we use weekly stock market returns in Australia, Singapore, the UK, and the US for MGARCH model with dummy variables with special focus on Australian stock market. Furthermore, this study uses the period from the first week of September 1998 to the last week of December 1998 as the 1998 global financial crisis, which is also used by Ellis and Lewis (2001) though Asian crisis started in 1997. In addition, Asian financial crisis largely spread outside Asia late 1998 (Bank for International Settlements 1999). This study selects the third week of September 2008 as the breaking point of the 2008 global financial crisis as global risk aversion of this financial crisis sharply increased following the Lehman collapse on 15 September 2008 (Frank & Hesse 2009).

The Australian stock market is of particular attention in this study as it is a major player in the Asia-Pacific region but relatively small compared to the US and the UK. According to the monthly report of Standard & Poor's (November 2008), Australian Securities Exchange (ASX) is the eighth largest in the world in terms of total market capitalization and the second largest in the Asia-Pacific region. Although Japanese market is the largest stock market in the Asia-Pacific region, this study excludes Japanese stock market from the analysis because previous studies find that the Australian stock market is not highly correlated with the Japanese market (McNelis 1993, Brooks & Henry 2000, Valadkhani *et al.* 2008). However, those studies find greater than 0.50 pair-wise correlations between Australia and the UK, Singapore, and the US.

The rest of this paper is organized as follows; Section II presents the literature review followed by the methodology in Section III. The data and preliminary findings are set out in Section IV. Section V discusses empirical econometric results. The last section provides some concluding remarks.

II Literature Review

When modelling volatility in financial data, the time-varying variance and covariance makes linear econometric models inappropriate. However, Engle's autoregressive conditional heteroskedasticity (ARCH) process (1982) and its generalisation (GARCH) model of Bollerslev (1986) are capable of capturing most of the non-linearity in the financial data. A multivariate framework of these univariate ARCH/GARCH models have now been widely used for analysing volatility transmission across different markets and assets since the volatility of financial markets move together across assets and markets (Bollerslev *et al.* 1992, Bollerslev *et al.* 1994). As such, MGARCH models have recently been used for analysing volatility co-movements and spillovers effects across international stock markets and identifying the significant influence from the US market to other markets (Theodossiou & Lee 1993, Theodossiou *et al.* 1997, Chou *et al.* 1999, Brooks & Henry 2000). The most commonly used MGARCH specifications are referred to as the vector GARCH (VECH) model of Bollerslev *et al.* (1988), the Constant Conditional Correlation (CCC) model of Bollerslev (1990) and the BEKK model of Engle and Kroner (1993).

For studying influence from financial crises, empirical studies have been applied different methodologies to capture the nature of volatility transmission across international markets resulting from financial crises. For instance, Ellis and Lewis (2001) applied a vector autoregression (VAR) model for Australian and New Zealand stock market data spanning from the beginning of 1994 to the end of August 1999. They found that shocks arising in the US market and own markets increased the volatility in both Australian and New Zealand stock markets more than the shocks arising in the Asian crisis economies during 1997 financial crisis. However, empirical evidence has shown that multivariate the ARCH-in-Mean model is better than the traditional VAR models and VAR-GARCH models (Polasek & Ren 2001). Furthermore, Polasek and Ren analysed volatility transmission during the 1997 Asian crisis using daily data of the US, Germany and Japan stock markets for a period of 2 years spanning from 21 June 1996 to 22 June 1998. They identified that different volatility transmission patterns among the stock markets of the US, Germany and Japan before and after the Asian crisis in 1997.

In addition, Theodossiou *et al.* (1997) use multivariate GARCH application identifying that the US market had less volatility during the post-October 1987 crisis, however, the volatility in the UK and Japan was the same during both pre and post-October 1987 periods. They have extended the CCC model by incorporating structural dummies for the 1987 financial crisis using weekly stock market returns in the US, the UK, and Japan for the period starting from 4 May 1984 to 21 October 1994. Finally, Caporale *et al.* (2006) use the BEKK model and likelihood ratio for causality-in-variance with bootstrapped critical values for different samples of daily data from the US, Japan, European and South East Asian stork markets covering 1997 South East Asia financial crisis.

III Methodology

The major objective of this paper is to examine the interdependence of return and co-volatility across four highly integrated international stock markets due to financial crisis, with a particular focus on Australia, by using the diagonal VECH model. The diagonal VECH model is of particular interest as it allows the conditional variance covariance matrix of stock market returns to vary over time and is more flexible compared to BEKK model if there are more than two variables in the conditional variance covariance matrix (Scherrer & Ribarits 2007). Empirical implementation of the VECH model is, however, limited due to the difficulty of guaranteeing a positive semi-definite conditional variance covariance matrix (Engle & Kroner 1993, Kroner & Ng 1998, Brooks & Henry 2000). Therefore, this study uses the unconditional residual variance as the pre-sample conditional variance to guaranteeing the positive semi-definite of conditional variance covariance matrix of the diagonal VECH model incorporating dummy variables.

Two dummies are used to test for the behaviour of stock market returns and volatility during global financial crises occurred in 1998 and 2008. The vector autoregressive stochastic process of assets returns is given in equation 1, which is the mean equation. Asset returns of country *i* (r_{iit}) are specified as a function of their own innovations (ε_{it}) and the past own return (r_{ijt-1}), for all $j = 1, \ldots, 4$ and $i = j$ as well as the lagged returns of other countries (r_{ijt-1}) for all $j = 1, .., 4$ and $i \neq j$ as follows:

$$r_{iit} = \mu_{0i} + \delta_{98i} D_{98} + \delta_{08i} D_{08} + \sum_{j=1}^{4} \mu_{ij} r_{ijt-1} + \varepsilon_{it} \quad (1)$$

where $i = 1$ for Australia, $i = 2$ for Singapore, $i = 3$ for the UK, and $i = 4$ for the US; μ_{0i} is the intercept for country *i*; μ_{ij} (for all *i* = 1, .. , 4 and *j* = 1, .. , 4*)* indicates the conditional mean of stock return, which represents the influence from own past returns of country *i* (i.e. own-mean spillovers) when $i = j$ and the influence from past returns of country *j* towards country *i* (i.e. cross-mean spillovers from country *j* to *i*) when $i \neq j$; and ε_{it} is own innovations (shocks) to country *i*. D_{98} dummy variable takes value 1 for 1998 global financial crisis (period from the first week of September 1998 to last week of December 1998) and 0 otherwise. Similarly, D_{08} dummy variable takes value 1 for 2008 global financial crisis (period from 15 September 2008 onwards) and 0 otherwise. δ_{98} and δ_{08} are corresponding coefficient of dummy variables D_{98} and D_{08}. The intercept of mean equation (1) for 1998 crisis is $\mu_{0i} + \delta_{98i}$ and for 2008 crisis is $\mu_{0i} + \delta_{08i}$ for each country *i*. In addition, significant positive values of δ_{98} and δ_{08} indicate that increase of respective measures during global financial crisis.

The conditional variance-covariance matrix (H_t) has four dimensions with the diagonal and non-diagonal elements representing the variance and the covariance terms, respectively. In matrix notation, H_t can be written as:

$$H_t = \begin{pmatrix} h_{11t} & h_{12t} & h_{13t} & h_{14t} \\ h_{21t} & h_{22t} & h_{23t} & h_{24t} \\ h_{31t} & h_{32t} & h_{33t} & h_{34t} \\ h_{41t} & h_{42t} & h_{43t} & h_{44t} \end{pmatrix} \quad (2)$$

where h_{iit} is a conditional variance at time *t* of the stock return of country *i* and h_{ijt} denotes the conditional covariance between the stock returns of country *i* and country *j* (where $i \neq j$) at time *t*.

Since H_t contains four variables, this study uses a diagonal VECH model (Bollerslev *et al.* 1988) as it is more flexible for more than two variable (Scherrer & Ribarits 2007). Furthermore, this model is based on the assumption that the conditional variance depends on squared lagged residuals and the conditional covariance depends on the cross-lagged residuals and lagged covariances of other series (Harris & Sollis 2003). In addition, we incorporate two structural dummies and $\frac{1}{2}N(N+1)\times 1$ vector of the corresponding diagonal VECH model can be written as follows:

$$vech(H_t) = C + G_{98}D_{98} + G_{08}D_{08} + A^{*}vech(\varepsilon_{t-1}\varepsilon'_{t-1}) + B^{*}vech(H_{t-1}) \qquad (3)$$

where A^* and B^* are $\frac{1}{2}N(N+1)\times\frac{1}{2}N(N+1)$ diagonal matrix of parameter, which satisfies $A^* = diag[vech(A)]$ and $B^* = diag[vech(B)]$ where A and B are $N\times N$ symmetrical matrices; and C, G_{98} and G_{08} are $\frac{1}{2}N(N+1)\times 1$ vectors of parameters. The diagonal elements of matrix A (a_{11}, a_{22}, a_{33} and a_{44}) measures the own-volatility shocks, which represent the influences from past squared innovations on the current volatility while non-diagonal elements (a_{ij} where $i \neq j$) determine the cross-volatility shocks, which is the cross product effects of the lagged innovations on the current covolatility. Similarly, the diagonal elements of matrix B (b_{11}, b_{22}, b_{33} and b_{44}) determine the own-volatility spillovers that is the influences from past squared volatilities on the current volatility and non-diagonal elements (b_{ij} where $i \neq j$) measure the cross-volatility spillovers that is the cross product effects of the lagged covolatilities on the current covolatility. The intercept of variances for 1998 global financial crisis is $c_{ii} + g_{98ii}$ and for 2008 crisis is $c_{ii} + g_{08ii}$ for each country *i*. Correspondingly, the intercept of covariances between country *i* and *j* for 1998 crisis is $c_{ij} + g_{98ij}$ and for 2008 crisis is $c_{ij} + g_{08ij}$ for all $i \neq j$. In addition, the significant positive values of g_{98ij} and g_{08ij} for all *i* and *j* indicate that increase of respective measures during 1998 and 2008 global financial crisis periods.

The number of parameters to be estimated and the positive semi-definiteness of the variance covariance matrix are two major issues to be considered in the estimation process of VECH model (Goeij & Marquering 2004). Bollerslev *et al.* (1988) and Goeij and Marquering (2004) suggest to use a diagonal version of *A* and *B* matrices to reduce the number of parameters in the estimation procedure. In addition, the conditional variance and covariance matrix in the diagonal VECH model is positive semi-definite if all of the parameters contained in A, B and C are positive and the initial conditional variance and covariance matrix (H_0) is also non-negative (Bauwens *et al.* 2006). According to, Bauwens *et al.* positive semi-definiteness of the conditional variance and covariance matrix can be easily derived by expressing the model in terms of Hadamard products or imposing conditions using the Cholesky factorization of the parameter. In this study, we impose conditions on the initial values as suggested by Bollerslev *et al*. (1988) and use the maximum likelihood function to generate these parameter estimates.

In this regard, let θ be a parameter of interest for a sample of *T* observations, then the log likelihood function will be:

$$L_T(\theta) = \sum_{t=1}^{T} l_t(\theta) \qquad (4)$$

where $l_t(\theta) = \frac{N}{2}\ln(2\pi) - \frac{1}{2}\ln|H_t| - \frac{1}{2}\varepsilon'_t H_t^{-1}\varepsilon_t$

According to Bollerslev *et al.* (1988), pre-sample values of θ can be set to be equal to their expected value of zero. However, in this study the unconditional variance of residuals is used as the pre-sample conditional variance to guarantee that H_t is positive semi-definite. The BHHH (Berndt Hall and Hall and Hausman) iterative algorithm is used to obtain the optimal values of our parameters by utilizing the following equation proposed by Engle and Kroner (1993):

$$\theta^{(i+1)} = \theta^{(i)} + \lambda_i \left(\left(\frac{\partial l_t}{\partial \theta} \right)' \frac{\partial l_t}{\partial \theta} \right)^{-1} \left(\frac{\partial l_t}{\partial \theta} \right)' \qquad (5)$$

where $\theta^{(i)}$ denotes the parameter estimate after the i^{th} iteration; $\frac{\partial l_t}{\partial \theta}$ is evaluated at $\theta^{(i)}$ and λ is a variable step length chosen to maximize the likelihood function in the given direction, which is calculated from a least squares regression of a $T \times 1$ vector of ones on $\frac{\partial l_t}{\partial \theta}$.

To test any remaining ARCH effects in the model we use the Ljung-Box test statistic (Hosking 1980), which is a multivariate version of the Portmanteau test. The Ljung-Box test statistic for a multivariate process of order (*p*, *q*) and a stationary time series $\{y_t : t = 1, 2, ..., T\}$ is given in the following equation:

$$Q = T^2 \sum_{j=1}^{s} (T - j)^{-1} tj \left\{ C_{Y_t}^{-1}(0) C_{Y_t}(j) C_{Y_t}^{-1}(0) C'_{Y_t}(j) \right\} \qquad (6)$$

where $Y_t = vech(y_t y_t')$; $C_{Y_t}(j)$ is the sample autocovariance matrix of order *j*; *s* is the number of lags being tested and *T* is the number of observations. The Ljung-Box test statistic, *Q*, is distributed asymptotically as a Chi-squared distribution for large samples under the null hypothesis of no ARCH effect. Replacing y_t by standardised residuals can be used to detect misspecification in the conditional variance matrix (Bauwens *et al.* 2006).

IV Data and Preliminary Findings

Average weekly stock market price indices for the period spanning from 6 January 1992 to 21 June 2009 (*n* = 910 observations) are used in this paper. Weekly data provide a number of advantages over the use of daily data. Firstly, it avoids the interferences associated with the use of synchronised data as the trading day of one country may coincide with a public holiday in another country. Secondly, it also avoids the time zone differences due to the four countries being located in various time zones with associated different opening and closing times. Some other similar studies have also preferred to use weekly data for the same reasons (Theodossiou & Lee 1993, Theodossiou & Lee 1995, Theodossiou *et al.* 1997, Brooks & Henry 2000, Ng 2000).

Based on the stock market price indices the stock market return (r_t) at time *t* is calculated as:

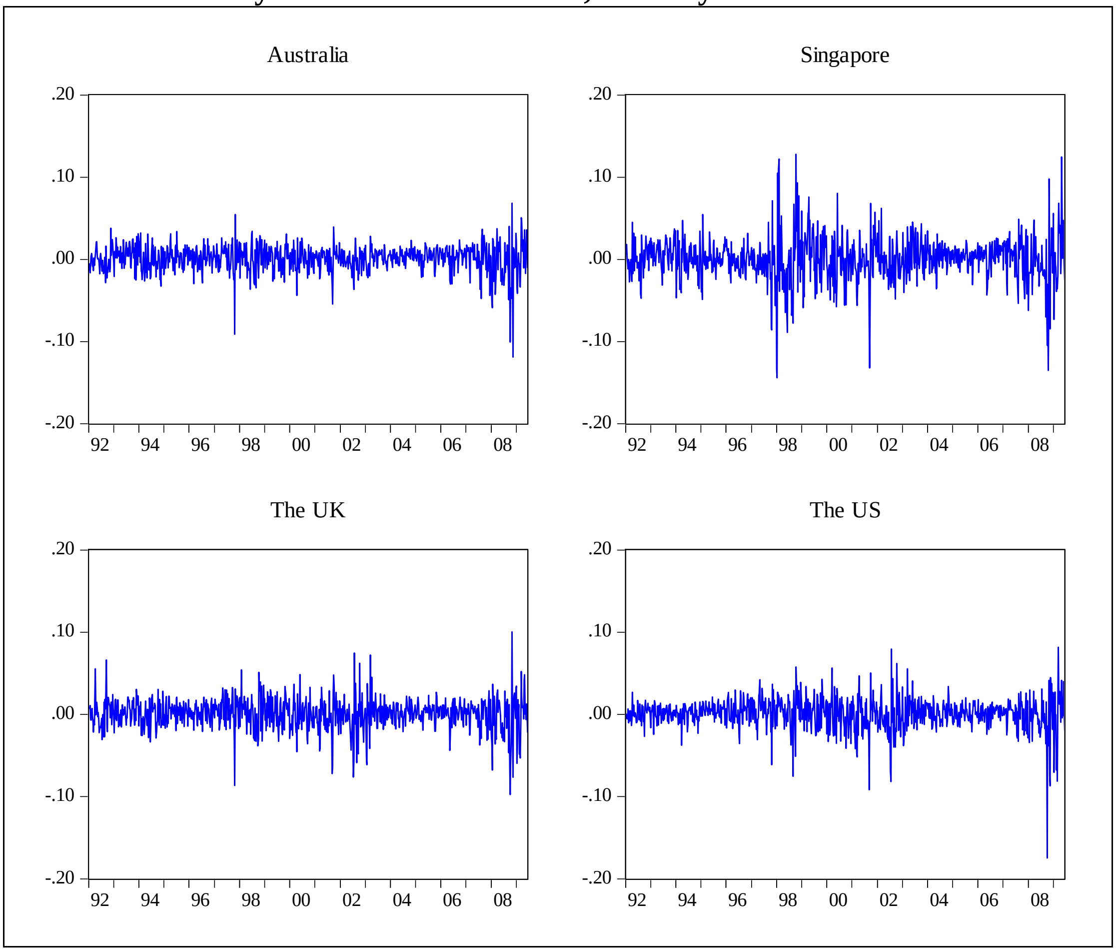
$$r_t = \ln \left(\frac{p_t}{p_{t-1}} \right) \qquad (7)$$

where p_t be the stock market price index at time *t*.

The stock market indices used in this study comprise the All Ordinaries Index (AORD) of Australia, the Straits Times Index (STI) of Singapore, the Financial Times Stock Exchange Index (FTSE100) of the UK and the Standard and Poor's 500 Index (S&P 500) of the US. However, it should be noted that the STI did not contain the data for two weeks covering the period from 14 January 2008 to 26 January 2008. To ensure continuity in the time series data, this minor gap was eliminated by interpolating the missing two values. Due to the terrorist attack in the US on 11 September 2001, data for the week beginning from 17 September 2001 to 21 September 2001 was absent from the US data. This one-week missing value was similarly approximated by interpolating the adjacent two values.

Table 1 presents the descriptive statistics for each stock market return series. The positive mean returns for the four stock markets range from a minimum 0.0005 (Singapore) to a maximum 0.0009 (Australia and the US) respectively. The sample standard deviations suggest that the Australian stock return is the least volatile series with a standard deviation of 0.0163, while the Singapore stock return can be considered as the most volatile series with a standard deviation of 0.0270. The corresponding measures for the UK (0.0192) and the US (0.0191) returns show that the volatility of these two series is almost the same. Furthermore, these findings confirm by the Figure 1 providing a visual perspective on the volatility of four return series over time during the sample period.

FIGURE 1. Weekly Stock Market Returns, January 1992 to June 2009



According to the estimated skewness statistics, all four return series show left skewness. The value of kurtosis is greater than 3.0 for all of the return series. As expected with any high frequency financial return series, this confirms a typical leptokurtic distribution, whereby return series are more peaked around the mean with a thicker tails compared to the normal distribution. The Jarque-Bera statistics also rejects the null hypothesis of normality at the 1 per cent level of significance reinforcing the above findings (see Table 1).

Table 1 also contains the pair-wise correlations among the four stock market returns. These estimated pair-wise correlation coefficients are all greater than 0.5 among the four stock markets suggesting that these markets are positively interrelated and significant at 1 per cent level. This finding is consistent with the previous findings of McNelis (1993) and Valadkhani *et al.* (2008). The highest correlation (0.7695) is between the stock market returns of the UK and the US, while the lowest (0.5141) is between the stock market returns of the US and Singapore. According to the correlation coefficients, the Australian stock return series is highly correlated with both the US and UK stock returns with approximately 0.65 correlation coefficients.

TABLE 1. Descriptive Statistics for Return Series

Descriptive Statistic	Australia	Singapore	The UK	The US
Mean	0.0009	0.0005	0.0006	0.0009
Median	0.0025	0.0009	0.0022	0.0025
Maximum	0.0685	0.1278	0.1005	0.0818
Minimum	-0.1189	-0.1440	-0.0973	-0.1747
Std. Dev.	0.0163	0.0270	0.0192	0.0191
Skewness	-1.1305	-0.2669	-0.4275	-1.3650
Kurtosis	9.2261	7.9919	6.3993	13.4794
Jarque-Bera	1663.647	955.654	465.853	4446.525
Correlation Coefficients				
AU	1.0000			
SI	0.5362	1.0000		
UK	0.6505	0.5325	1.0000	
US	0.6626	0.5141	0.7695	1.0000

Sources: AORD index (Australia), the STI (Singapore), the FTSE100 (the UK) and the S&P500 (the US) for the period 6 January 1992 - 21 June 2009, containing 910 observations and downloaded from www.finance.yahoo.com.au

The Augmented Dickey-Fuller (ADF) test results given in the Table 2 suggest that we can reject the null hypothesis of the presence a unit root in the data at the 5 per cent level. This implies that all of our four return series are stationary. We also examined the Ljung-Box test statistic of four return series under the null hypothesis of no serial correlation. According to the test results using up to 24 lags, we can reject the null hypothesis of no serial correlation at the 1 per cent level of significant for all the series. These results provide strong evidence of serial correlation in the four series, justifying the inclusion of the lag terms in equation (1).

TABLE 2. ADF Test Results and Ljung-Box Q-Statistic Results for Weekly Stock Market Returns

	Australia		Singapore		UK		US	
ADF *t* statistics								
Based on min. AIC	-15.18		-11.53		-20.35		-11.20	
Based on min. SIC	-15.18		-11.53		-24.29		-24.93	
Ljung-Box test statistics for return series								
	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value
Q(1)	44.22	0.00	57.60	0.00	41.64	0.00	33.02	0.00
Q(2)	44.66	0.00	58.91	0.00	42.12	0.00	33.05	0.00
Q(3)	49.80	0.00	76.43	0.00	43.06	0.00	34.09	0.00
Q(4)	49.93	0.00	77.04	0.00	45.10	0.00	36.13	0.00
Q(5)	50.77	0.00	78.85	0.00	45.35	0.00	37.41	0.00
Q(6)	52.31	0.00	83.11	0.00	45.73	0.00	41.02	0.00
Q(7)	55.39	0.00	83.14	0.00	47.73	0.00	43.76	0.00
Q(8)	55.39	0.00	83.69	0.00	48.31	0.00	47.59	0.00
Q(9)	59.17	0.00	83.71	0.00	48.32	0.00	47.67	0.00
Q(10)	59.18	0.00	83.77	0.00	48.60	0.00	47.78	0.00
Q(11)	59.20	0.00	84.11	0.00	49.59	0.00	52.54	0.00
Q(12)	59.63	0.00	84.13	0.00	50.05	0.00	52.71	0.00
Q(13)	59.67	0.00	84.14	0.00	50.79	0.00	53.21	0.00
Q(14)	62.55	0.00	84.39	0.00	51.23	0.00	56.48	0.00
Q(15)	66.10	0.00	84.56	0.00	51.24	0.00	60.27	0.00
Q(16)	66.12	0.00	84.73	0.00	51.28	0.00	60.27	0.00
Q(17)	66.13	0.00	85.33	0.00	51.37	0.00	60.30	0.00
Q(18)	67.53	0.00	85.39	0.00	57.76	0.00	61.06	0.00
Q(19)	67.63	0.00	85.47	0.00	58.03	0.00	61.20	0.00
Q(20)	67.69	0.00	85.47	0.00	58.04	0.00	63.72	0.00
Q(21)	68.00	0.00	86.45	0.00	59.67	0.00	70.86	0.00
Q(22)	68.69	0.00	90.32	0.00	62.25	0.00	73.45	0.00
Q(23)	68.82	0.00	90.33	0.00	62.45	0.00	73.73	0.00
Q(24)	74.46	0.00	93.84	0.00	62.54	0.00	75.16	0.00

Note: AIC = Akaike information criterion and SIC = Schwarz information criterion. Q(n) is the n^{th} lag Ljung-Box test statistics

V Empirical Results

We compared various diagonal VECH(*p*,*q*) specifications, where p = 1, 2, and 3 and q = 1, 2, and 3[1] under the Akaike Information Criterion (AIC), Schwarz Information Criterion (SIC) and Hannan-Quinn Information Criterion (HIC). The results indicate that the diagonal VECH(1,1) specification has consistently the lowest AIC (-23.11), SIC (-22.69) and HIC (-22.95) with a log-likelihood of 10583.36. Therefore, in this study we adopted the diagonal VECH(1,1) specification with structural dummies and corresponding results for the equation (3) with the conditional mean equation (1) are given in Table 3.

According to the estimated coefficients, the constant terms in mean equation are statistically significant for all four countries. However, the coefficient of dummy variables in the mean equation for 1998 and 2008 crises are statistically insignificant

[1] These results have not been reported in this paper but they are available from the authors upon request.

for all four countries suggesting that these two recent global financial crises do not influence mean returns of these four markets. The own-mean spillovers (μ_{ii} for all i= 1,..,4) are statistically significant for all four markets, providing evidence of an influence on current returns of each stock market arising from their first lag returns (r_{iit-1}). The own-mean spillovers vary from a minimum of 0.1377 (Australia) to a maximum of 0.2059 (the US). Significant positive cross-mean spillovers effects exist from the US to all three markets. However, an important finding is that there is no positive and significant impact in the opposite direction. This impact is lowest for the UK (0.0978). The significant cross-mean spillovers impact from the US to Singapore (0.1374) is slightly lower than that of Australia (0.1460). In addition, Singapore market is also positively influenced by the UK returns. However, the impact from the UK (0.0996) is much lower than that from the US. In other words, past US stock market returns have greater impact on the Singapore stock market than the UK market returns. Table 3 also presents the R_i^2 values, which is calculated as $1-[\mathrm{var}(\varepsilon_{it})/\mathrm{var}(r_{iit})]$. This measures the predictability of variations of future stock market returns due to the conditional mean spillovers. Similar to Theodossiou and Lee (1993), these R_i^2 are less than 10 per cent, indicating very low explanatory power.

The coefficients of constant terms for both variance and covariance equations of each market are statistically significant. Furthermore, the estimated dummy coefficients for the 1998 global financial crisis in the variance and covariance equations are insignificant for all four markets suggesting that the 1998 global financial crisis did not have any significant influence on variance and covariance structure of these four markets. In other words, though Asian financial crisis spread outside the Asia during end 1998, it did not significantly impact on stock market volatility and covolatility among these four countries for the entire period starting from the first week of September 1998 to last week of December 1998.

However, coefficients for dummy variables for the 2008 global financial crisis in the variance equations are positive and significant for all four markets except for the UK. This suggests that the recent global financial crisis in 2008 increased the volatility in stock markets of Australia, Singapore, and the US. The lowest dummy coefficient of Australian market (0.000095) and the highest dummy coefficient for the Singapore market (0.000304) indicate the greater influence on Singapore market from this ongoing financial crisis. On the other hand, the dummy coefficients in covariance equations are all positive and statistically significant suggesting that 2008 financial crisis contributes to increase covolatilities across these four markets. The lowest dummy coefficient in covariance equation is 0.000088 between Australia and the UK while it is higher between Singapore and the US (0.000174). In addition, the dummy coefficient in covariance between UK and Singapore (0.000169) is higher than that of Australia. These respective measures indicate the greater impact on Singapore market than the Australian market during the 2008 global financial crisis.

TABLE 3. Parameter Estimation for the Mean Equation and the Diagonal VECH(1,1) Specification

$$r_{iit} = \mu_{0i} + \delta_{98i} D_{98} + \delta_{08i} D_{08} + \sum_{j=1}^{4} \mu_{ij} r_{ijt-1} + \varepsilon_{it}$$

$$vech(H_t) = C + G_{98} D_{98} + G_{08} D_{08} + Avech(\varepsilon_{t-1}\varepsilon'_{t-1}) + Bvech(H_{t-1})$$

Parameter	Australia		Singapore		UK		US	
	Coefficient	*t*-ratio	Coefficient	*t*-ratio	Coefficient	*t*-ratio	Coefficient	*t*-ratio
Parameter Estimation for Mean Equation								
μ_{0i}	0.001822***	4.46	0.001337**	2.28	0.001566***	3.22	0.001945***	4.35
δ_{98i}	0.004552	1.05	0.018344	1.56	0.003338	0.62	0.008836	1.59
δ_{08i}	-0.006021	-0.99	-0.006028	-0.63	-0.007617	-1.12	-0.007924	-0.81
μ_{i1}	0.137684***	3.47	-0.016888	-0.33	-0.042502	-1.00	-0.097205**	-2.36
μ_{i2}	-0.011335	-0.52	0.182226***	5.30	-0.018246	-0.79	0.005751	0.26
μ_{i3}	0.012184	0.37	0.099566*	1.83	0.148459***	3.28	0.019916	0.48
μ_{i4}	0.145995***	3.83	0.137426**	2.47	0.097835**	2.18	0.205907***	4.49
Parameter Estimation for Variance Equation								
c_{i1}	0.000005**	2.63						
c_{i2}	0.000005**	2.57	0.000012**	2.96				
c_{i3}	0.000003**	2.39	0.000005**	3.06	0.000006**	3.09		
c_{i4}	0.000002**	2.39	0.000003**	2.37	0.000003**	3.03	0.000004**	3.14
g_{98i1}	-0.000003	-0.20						
g_{98i2}	0.000014	0.44	0.000146	0.76				
g_{98i3}	0.000004	0.24	0.000072	1.16	0.000031	0.74		
g_{98i4}	0.000003	0.26	0.000006	0.22	0.000006	0.30	-0.000006	-0.34
g_{08i1}	0.000095*	1.76						
g_{08i2}	0.000170*	1.85	0.000304*	1.78				
g_{08i3}	0.000088*	1.80	0.000169**	1.93	0.000110	1.64		
g_{08i4}	0.000112**	2.14	0.000174**	1.93	0.000132*	1.90	0.000180**	2.36
a_{i1}	0.052158***	4.29						
a_{i2}	0.040253***	3.67	0.091812***	5.40				
a_{i3}	0.038079***	4.31	0.038517***	3.79	0.052414***	5.53		
a_{i4}	0.036398***	4.68	0.035579***	3.64	0.042934***	5.72	0.050720***	5.45
b_{i1}	0.920445***	49.05						
b_{i2}	0.907779***	35.86	0.878267***	42.03				
b_{i3}	0.933683***	55.93	0.912127***	49.32	0.919825***	62.98		
b_{i4}	0.940860***	68.81	0.932989***	54.83	0.932134***	78.04	0.926858***	69.82
$a_{ii} + b_{ii}$	0.972603		0.970079		0.972239		0.977578	
R_i^2	0.090806		0.099984		0.056606		0.055316	

Notes: (a) i = 1 for Australia, i = 2 for Singapore, i = 3 for the UK and i = 4 for the US. (b) *** indicates that statistically significant at 1 per cent level, ** indicates that statistically significant at 5 per cent level and * indicates that statistically significant at 10 per cent level

Significant own-volatility shocks for all four markets (a_{11}, a_{22}, a_{33} and a_{44}) indicate the presence of ARCH effects in these four markets. This effect varies from 0.0507 (the US) to 0.0918 (Singapore). This means that the past shocks arising from the Singapore market will have the strongest impact on its own future market volatility compared to the shocks stemming from the other three markets. Based on the magnitudes of the estimated cross-volatility coefficients, a_{ij} ($i \neq j$), innovations in all of the four stock markets influence the volatility of other markets, but the own-volatility shocks, a_{ij} ($i = j$), are generally higher than the cross-volatility shocks. This suggests that past country-specific shocks (lagged ARCH effects) have a stronger effect on their own future volatility than past volatility shocks arising from other markets. According to the results, the degree of cross-volatility shocks is pair-wise the weakest between Singapore-the US (0.0356) and the strongest between the US-the UK (0.0429). We also found the evidence of volatility shock persistence emanating from all of the other three markets to Australia. This cross volatility persistence between Australia on one hand and Singapore, the UK, and the US on the other are 0.0403, 0.0381, and 0.0364, respectively.

The estimated coefficients for the variance-covariance matrix (equation 3) have also been presented in Table 3. The b_{ij} ($i = j$) coefficients for the one-lag conditional variance for all markets are statistically significant and positive. These findings are consistent with similar studies in the literature (Theodossiou & Lee 1993, Worthington & Higgs 2004) indicating the presence of high volatility persistence in the four markets. The own-volatility spillovers effect is lowest in Singapore $(b_{22} = 0.8783)$ and the highest in the US market $(b_{44} = 0.9269)$. This implies that the past volatility in the US market will have the strongest impact on its own future volatility compared to the other three markets. Furthermore, the significant nonzero b_{ij} coefficients (where $i \neq j$ for all i and j) indicates further evidence for high and positive volatility spillovers persistence across these well-integrated markets. The significant cross volatility effect presents between Australia those of Singapore, the UK, and the US are 0.9078, 0.9337, and 0.9409, respectively. This supports the evidence of volatility persistence emanating from all of the other three markets to Australia. Furthermore, cross-volatility persistence for Singapore, stemming from the UK and the US, are 0.9121 and 0.9330, respectively. In this respect, the most influential market would appear to be the US and it influences the Australian market than Singapore market. The sum of the lagged ARCH and GARCH coefficients ($a_{ii} + b_{ii}$) for Australia, Singapore, the UK and the US are 0.9726, 0.9701, 0.9722 and 0.9776, respectively. These values support the assumption of covariance stationarity and the volatility persistence in the data as they are very close to unity.

Table 4 presents the normality test statistics, the unit root test results, and Ljung-Box test statistics for the standardised residual series of the model. Due to the nature of financial data the resulting residuals are not normally distributed, however, based on the skewness and kurtosis statistics the standardized residuals are closer to a normal distribution than the original return series. According to the ADF test results, all four standardised residual series are stationary. Similar to return series, the Ljung-Box test statistic of four standardised residual series were examined under the null hypothesis of no serial correlation. These results are also given in the Table 4. According to the calculated Ljung-Box test statistics for standardised residual series up to 24 lags, we did not find the evidence of serial correlation in the Australian and the US market. However, for standardised residual series of both Singapore and the UK indicate the serial correlation from second lag to fifth lag. However, the standardised residuals of these two markets do not show any higher order serial correlation.

TABLE 4. Diagnostic Tests on the Standardized Residuals of the Model

	Australia		Singapore		UK		US	
Statistics on standardized residuals								
Skewness	-0.52		-0.21		0.13		-0.24	
Kurtosis	4.69		3.97		3.86		5.00	
Jarque-Bera	148.77		42.70		30.54		160.34	
ADF *t* statistics								
Based on min. AIC	-29.86		-15.38		-22.34		-18.81	
Based on min. SIC	-29.86		-28.88		-28.25		-29.71	
Ljung-Box test statistics for standardized residuals								
	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value
Q(1)	0.06	0.81	1.61	0.21	3.96	0.05	0.21	0.65
Q(2)	0.46	0.80	7.35	0.03	8.88	0.01	0.50	0.78
Q(3)	3.23	0.36	11.05	0.01	10.91	0.01	4.82	0.19
Q(4)	4.57	0.33	12.24	0.02	10.92	0.03	4.86	0.30
Q(5)	4.74	0.45	12.31	0.03	11.48	0.04	6.23	0.29
Q(6)	4.79	0.57	12.31	0.06	11.71	0.07	6.27	0.39
Q(7)	5.64	0.58	12.41	0.09	12.36	0.09	6.27	0.51
Q(8)	5.74	0.68	12.44	0.13	12.45	0.13	6.30	0.61
Q(9)	7.37	0.60	12.52	0.19	12.65	0.18	6.31	0.71
Q(10)	7.37	0.69	13.19	0.21	12.68	0.24	6.56	0.77
Q(11)	7.43	0.76	13.84	0.24	14.36	0.21	6.61	0.83
Q(12)	8.32	0.76	14.14	0.29	14.42	0.28	6.80	0.87
Q(13)	8.52	0.81	14.18	0.36	14.81	0.32	8.03	0.84
Q(14)	9.43	0.80	14.19	0.44	14.91	0.38	8.23	0.88
Q(15)	9.83	0.83	14.39	0.50	15.65	0.41	8.80	0.89
Q(16)	10.84	0.82	16.70	0.41	17.31	0.37	8.84	0.92
Q(17)	11.18	0.85	19.54	0.30	18.07	0.38	9.67	0.92
Q(18)	11.55	0.87	19.78	0.35	18.51	0.42	11.35	0.88
Q(19)	13.28	0.82	19.86	0.40	20.04	0.39	11.49	0.91
Q(20)	13.45	0.86	20.03	0.46	20.09	0.45	11.53	0.93
Q(21)	13.55	0.89	20.30	0.50	20.64	0.48	12.30	0.93
Q(22)	14.08	0.90	21.41	0.50	20.89	0.53	12.32	0.95
Q(23)	14.97	0.90	22.78	0.47	24.44	0.38	12.46	0.96
Q(24)	15.91	0.89	22.82	0.53	28.86	0.23	12.62	0.97

Note: Q(n) is the n^{th} lag Ljung-Box test statistics

We also estimated the Portmanteau Box-Pierce/Ljung-Box Q-statistics and the adjusted Q-statistics for the standardised system residuals using the Cholesky of covariance Orthogonization method and results are presented in the Table 5. Similar to above findings, both the Q-statistics and the adjusted Q-statistics support the null hypothesis of no autocorrelations at the 5 per cent level for various lags of up to 24, with the only exception being the third lag. Thus, one can conclude that there is no significant amount of serial correlation left in higher order system residuals as the bulk of the serial correlation observed in Table 2 (original return series) has now disappeared in the resulting system residuals in Table 5. This provides further support for the VECH model as it absorbs a great deal of inertia and ARCH and GARCH effects present in the original return series.

TABLE 5. The Results of System Residual Portmanteau Tests for Autocorrelations Using the Cholesky Orthogonalization Method

Autocorrelation coefficients	Q-Stat	p-value	Adj. Q-Stat	p-value	d.f
Q(1)	17.32	0.37	17.34	0.36	16
Q(2)	41.21	0.13	41.28	0.13	32
Q(3)	64.73	0.05	64.88	0.05	48
Q(4)	76.46	0.14	76.66	0.13	64
Q(5)	94.56	0.13	94.86	0.13	80
Q(6)	112.69	0.12	113.11	0.11	96
Q(7)	122.32	0.24	122.81	0.23	112
Q(8)	133.56	0.35	134.15	0.34	128
Q(9)	148.18	0.39	148.93	0.37	144
Q(10)	165.65	0.36	166.59	0.34	160
Q(11)	184.08	0.32	185.24	0.30	176
Q(12)	200.88	0.32	202.27	0.29	192
Q(13)	224.78	0.20	226.51	0.18	208
Q(14)	237.52	0.26	239.45	0.23	224
Q(15)	249.19	0.33	251.32	0.29	240
Q(16)	270.94	0.25	273.46	0.22	256
Q(17)	282.86	0.32	285.61	0.27	272
Q(18)	298.18	0.33	301.24	0.28	288
Q(19)	315.26	0.32	318.68	0.27	304
Q(20)	327.18	0.38	330.88	0.33	320
Q(21)	337.16	0.47	341.09	0.41	336
Q(22)	350.59	0.51	354.84	0.45	352
Q(23)	372.36	0.43	377.18	0.36	368
Q(24)	389.50	0.41	394.79	0.34	384

Note: Q(n) is the n^{th} lag Ljung-Box test statistics.

VI Summary and Conclusion

McNelis (1993) and Valadkhani *et al.* (2008) argue that the Australian stock market return is highly integrated with the stock market returns of the UK, Singapore, and the US. In addition, other studies have identified that financial crises cause volatility transmission pattern among different market (Theodossiou *et al.* 1997, Polasek & Ren 2001, Caporale *et al.* 2006, Tsouma 2007). This paper uses a multivariate diagonal VECH model with structural dummies for the 1998 global financial crisis and the 2008 global financial crisis to extend the existing literature by identifying the source and magnitude of mean and volatility spillovers across these four markets due to these more recent financial crises. We have used a general vector stochastic process of assets returns and allowed the lagged returns of each country to influence the Australian market.

Furthermore, we have incorporated dummy variables to capture difference in mean returns and volatility transmission due to more recent global financial crisis. We could not find any significant influence on the mean returns in all four markets resulting from these two global financial crisis. Similarly, results do not indicate a significant influence from the 1998 financial crisis on changing volatility and covolatility structure in all four markets. Similar to Theodossiou *et al.* (1997), Polasek and Ren (2001), and Caporale *et al.* (2006) we identify that different volatility and cross-volatility patterns in the four stock markets have emerged from the 2008 global financial crisis. Furthermore, our findings provide evidence that the 2008 global financial crisis contribute to increased stock return volatilities across all these four markets. This supports the findings of Schwert (1989) which says that stock market volatility tends to be high during financial crisis. More generally, we found that the positive return spillovers effects are only unidirectional and run from both the US and the UK (the bigger markets) to Australia and Singapore (the smaller markets). These results are consistent with the univariate GARCH application of Brailsford (1996) for Australia, New Zealand and the US and the multivariate GARCH application of Brooks and Henry (2000) for Australia, Japan, and the US, indicating that the lagged returns of the US stock market heavily influence the returns of the Australian stock market but not vice versa.

Based on the magnitude of the own volatility shocks (own innovation effects), it is found that compared to Australia, the US and the Singapore market is relatively more influenced from its own innovations, however, the shocks arising from the US market can indiscriminately impact on all of the other markets in our sample. As expected, it is also found that the own and cross volatility persistence do exist among these four markets. In addition, Singapore and the UK stock returns exhibit the lowest and highest magnitude of the own volatility persistence effect (the GARCH effect), respectively. This suggests that the larger a stock market, the higher would be the magnitude of that market's own volatility persistence. Based on our results one may also conclude that own-volatility spillovers are generally lower than cross-volatility spillovers from larger market to smaller markets. This would suggest that in such markets changes in volatility are more likely to emanate the volatility intertwined with global financial markets.

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