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Indika Karunanayake
University of Wollongong, indika@uow.edu.au

Abbas Valadkhani
University of Wollongong, abbas@uow.edu.au

Martin O'Brien
University of Wollongong

University of Wollongong
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Indika Karunanayake

Abbas Valadkhani

Martin O'Brien

School of Economics
University of Wollongong

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Indika Karunanayake, Abbas Valadkhani, Martin O'Brien

School of Economics, University of Wollongong, Australia

This paper examines the interplay between stock market returns and their volatility, focusing on the Asian and global financial crises of 1997-98 and 2008-09 for Australia, Singapore, the UK, and the US. We use a multivariate generalised autoregressive conditional heteroskedasticity (MGARCH) model and weekly data (January 1992-June 2009). Based on the results obtained from the mean return equations, we could not find any significant impact on returns arising from the Asian crisis and more recent global financial crises across these four markets. However, both crises significantly increased the stock return volatilities across all of the four markets. Not surprisingly, it is also found that the US stock market is the most crucial market impacting on the volatilities of smaller economies such as Australia. Our results provide evidence of 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. A high degree of time-varying co-volatility among these markets indicates that it is riskier for investors to diversify their financial portfolio by acquiring stocks within these four countries only.

I INTRODUCTION

The interaction between financial markets has increased with the integration of national economies through international trade and finance. The understanding of such cross-market linkages and interactions can be useful for the 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

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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.

The motivation for this paper relates to the identification of factors affecting the cross-country spillovers in the volatility of stock returns during the 1997 Asian and recent global financial crises. We have chosen the stock markets of Australia, Singapore, the UK, and the US because according to Valadkhani *et al.* (2008) and McNelis (1993), these four markets are highly integrated. In addition, one of the aims of this paper is to focus specifically on the cross-country spillover in volatility among the US (the biggest financial market in the world), the UK (the third largest, Standard & Poor's, 2008), and the major financial markets in the Asian-Pacific region.

It is important to compare and contrast the nature of the two crises in terms of their origins, their similarities, and perhaps their differences. Both crises were similar because over-leveraging, hence bad debts played an important common role in fomenting the crises. According to the Bank for International Settlements (BIS, 1999, 2009), the 1997-1998 crisis engulfed the global market with the collapse of Thai-baht but on the other hand the recent global financial crisis originated from the collapse of the US subprime mortgage market. Furthermore, inadequately supervised banking systems, asset price bubbles, increase of credit growth, over-expansion of the capital stock and rigid exchange rate regimes were recognized by the BIS as key issues for the countries affected with the 1997-1998 crisis. Similarly, the solvency of large parts of the global banking system, widespread increases in asset prices, easy credit conditions, and unusually low real interest rates were possible causes associated with the recent global financial crises (BIS, 2009). This study captures the fundamental differences between the two crises by using dummy variables in a Multivariate GARCH model to shed some light as how and where they originated. This enables us to explain whether cross-country spillovers in volatility were similar for the two financial crises.

The literature has shown that there are variations in the impact-timeline from market to market. For instance, the Asian financial crisis started in mid-1997 spreading within Asia until mid-1998 and subsequently engulfing Russia and other countries (BIS, 1999). Ellis and Lewis (2001) contend that financial market volatility in Australia and New Zealand was more pronounced in late 1998 than mid-1997, when the main events of Asian financial crisis occurred. According to Richardson (1998) and Garg *et al.* (1999), the Asian financial crisis had become a worldwide phenomenon on the 27th of October 1997 when the Dow Jones Industrial Average plunged 554.26 points. This decline was recorded as the largest fall ever at the time in terms of points and the second largest decline in terms of percentages.

Due to the disparity of impact-timeline, we have experimented with the exact timing of the dummies to test the timing of any possible effect on the four stock markets of interest to this study. Ultimately, we used the period starting from the first week of July 1997 to the last week of September 1998 to capture the Asian financial crisis. As for the more recent global financial meltdown, this paper considers the third week of September 2008 as the starting point of the crisis. The rationale is that this financial crisis became sharply out of control following the Lehman Brothers collapse on 15 September 2008 (Frank & Hesse 2009). Furthermore, this crisis is deemed to persist through until the end of the time period of analysis. That is, up to and including June 2009.

The rest of this paper is organized as follows; Section II presents our methodology, which is built upon the diagonal vector GARCH (DVECH)[1] model. The data and preliminary findings are set out in Section III followed by our empirical econometric results in Section IV. The last section provides some concluding remarks.

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[1] Diagonal vector GARCH (DVECH) (Bollerslev *et al.*, 1988).

II METHODOLOGY

The major intention of this paper is to examine the interdependence of return and co-volatility across four highly integrated international stock markets due to financial crises. We use the DVECH model augmented with two dummy variables to study volatility transmission across different stock markets during financial crises periods and non-financial crises periods. Similar dummy structure has also been used in some other studies (Longin & Solnik, 1995; Theodossiou *et al.*, 1997; Ellis & Lewis, 2001; Polasek & Ren, 2001).

Multivariate GARCH models are particularly relevant to the current study as Theodossiou *et al.* (1997) and many others suggest that this technique is capable of capturing the interaction effects within the conditional mean and variances of two or more series. This study uses the DVECH model, which is one of the many possible multivariate GARCH specifications, primarily because it allows the conditional variance covariance matrix of stock market returns (H_t) to vary over time. According to Bauwens *et al.* (2006), the DVECH model is also more appropriate for studying the dynamics of variances and covariances. Therefore, we extended this model allowing dummy variables to capture the effects of the two financial crises at different points in time. However, Engle and Kroner (1993) argued that the empirical implementation of the DVECH model is limited due to the difficulty of guaranteeing that matrix is a positive semi-definite. To maintain positive semi-definite of that matrix we impose conditions on the initial values as suggested by Bollerslev *et al.* (1988) and use ML methods to generate these parameter estimates. The conditional variance covariance matrix (H_t) for this study can be written as:

$$H_t = \begin{pmatrix} h_{11t} & h_{12t} & h_{13t} & h_{14t} \\ h_{21t} & h_{22t} & h_{23t} & h_{24t} \\ h_{31t} & h_{32t} & h_{33t} & h_{34t} \\ h_{41t} & h_{42t} & h_{43t} & h_{44t} \end{pmatrix} \tag{1}$$

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.

Furthermore, we use the BHHH (Berndt, Hall, Hall, & Hausman, 1974) algorithm to obtain the optimal values of our parameters and Ljung-Box test statistic to test any remaining ARCH effects in the model.

The vector autoregressive stochastic process of assets returns is given in equation (2), representing 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;

$$r_{iit} = \mu_{0i} + \delta_{97i} D_{97} + \delta_{08i} D_{08} + \sum_{j=1}^{4} \mu_{ij} r_{ijt-1} + \varepsilon_{it} \tag{2}$$

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, showing the influence from own past returns of country i (i.e. own-mean spillovers) when $i = j$; and the cross-mean spillovers from country j to i when $i \neq j$; and ε_{it} is referred to as own innovations (shocks) to country i. The D_{97} dummy variable captured the effect of the Asian crisis by taking the value 1 for the period from the first week of July 1997 to the last week of September 1998 and 0 otherwise. Similarly, the D_{08} dummy variable is included in the model to capture the more recent global financial crisis by taking the value 1 in the period from 15 September 2008 onwards and 0 otherwise as this crisis is deemed to be ongoing in our period of analysis. The coefficients δ_{97} and δ_{08} are the corresponding coefficients of dummy variables D_{97} and D_{08}. Therefore, intercept of mean equation (2) for the Asian crisis is postulated to be $\mu_{0i} + \delta_{97i}$ and for the global financial crisis would be $\mu_{0i} + \delta_{08i}$ for each country *i*.

The corresponding DVECH model into our framework which can be written as follows:

$$vech(H_t) = C + G^*_{97} D_{97} + G^*_{08} D_{08} + A^* vech(\varepsilon_{t-1}\varepsilon'_{t-1}) + B^* vech(H_{t-1}) \tag{3}$$

where A^*, B^*, G^*_{97} and G^*_{08} are $\frac{1}{2}N(N+1) \times \frac{1}{2}N(N+1)$ diagonal matrix of parameter, which satisfies $A^* = diag[vech(A)]$, $B^* = diag[vech(B)]$, $G^*_{97} = diag[vech(G_{97})]$ and $G^*_{08} = diag[vech(G_{08})]$ where *A*, *B*, G_{97} and G_{08} are $N \times N$ symmetrical matrices; and C is a $\frac{1}{2}N(N+1) \times 1$ vectors of parameters. The $vech(\cdot)$ operator denotes the column-stacking operator applied to upper portion of the symmetric matrix. The diagonal elements of matrix *A* (a_{11}, a_{22}, a_{33} and a_{44}) measure the own-volatility shocks, which represent the impacts arising from past squared innovations on the current volatility while non-diagonal elements (a_{ij} where $i \neq j$) determine the cross-volatility shocks, which can be shown as 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 can be considered as the past volatilities on the current volatility and finally the non-diagonal elements (b_{ij} where $i \neq j$) capture the cross-volatility spillovers which are the lagged covolatilities on the current co-volatility. The intercept of variances for the Asian and global financial crises for country *i* are $c_{ii} + g_{97ii}$ and $c_{ii} + g_{08ii}$, respectively. Correspondingly, the intercept of covariances between country *i* and *j* for the Asian crisis is $c_{ij} + g_{97ij}$ and for the global crisis is $c_{ij} + g_{08ij}$ for all $i \neq j$. In addition, the expected significant positive values of g_{97ij} and g_{08ij} for all *i* and *j* indicate that the crises are expected to have positive effects on the volatility and cross volatility.

III 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. Based on the stock market price indices, the stock market return (r_t) at time t is calculated as $r_t = \ln\left(\frac{p_t}{p_{t-1}}\right)$.

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 I 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 are confirmed by a cursory look at Figure 1, providing a visual perspective on the volatility of four return series over time during the sample period.

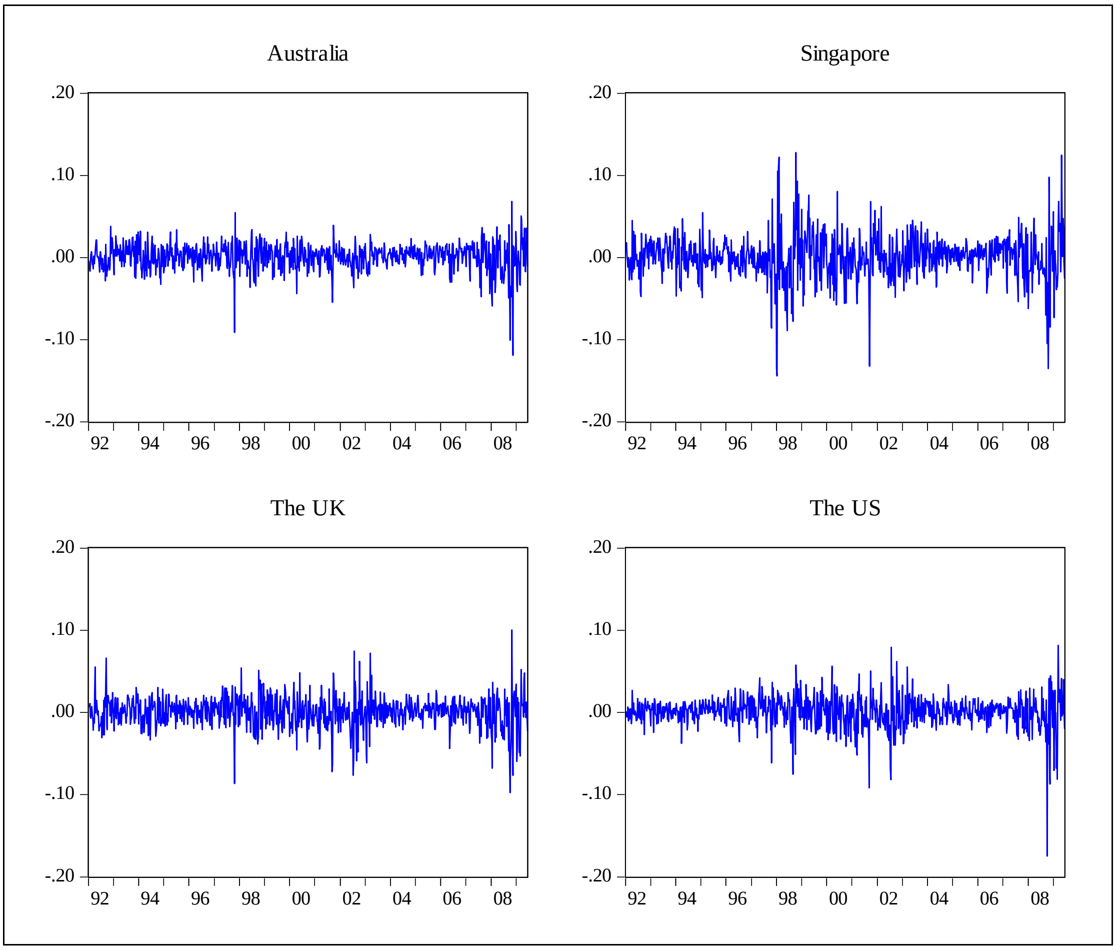

Figure 1. Weekly stock market returns from January 1992 to June 2009.

According to the estimated skewness statistics, all four return series are skewed to the left. Furthermore, 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 reject the null hypotheses of normality at the 1 per cent level of significance, reinforcing the above findings.

Table I. 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.

Table I 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 confirming that these markets are positively interrelated and significant at the 1 per cent level. This finding is also 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 a correlation coefficient of approximately 0.65. Furthermore, the results of the Augmented Dickey-Fuller (ADF) test and the Ljung-Box test given in the Table II suggest that that all of our four return series are stationary and serially correlated, justifying the inclusion of the lag terms in equation (2).

Table II. 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.

IV EMPIRICAL RESULTS

In this study we adopted the DVECH(1,1)[2] specification augmented with our dummy variables as discussed earlier in equations (2) and (3), with the results are presented in Table III. According to the estimated coefficients, the constant terms in the mean equation are statistically significant at the 1 per cent level for all four countries. However, the coefficient of the dummy variables in the mean equation for the 1997-98 Asian crisis is statistically insignificant for all four countries with the only exception being the Singapore returns which

[2] We tested various DVECH(p,q) specifications (where p = 1, 2, and 3 and q = 1, 2, and 3) using three model selection criteria, viz. the Akaike Information Criterion (AIC), Schwarz Information Criterion (SIC) and Hannan-Quinn Information Criterion (HIC). The results indicate that the DVECH(1,1) specification has consistently the lowest AIC (-23.13), SIC (-22.72) and HIC (-22.97) with a log-likelihood of 10593.61.

are significant at the 10 per cent level. The 2008-09 global crisis dummy was also statistically insignificant for all four countries. Thus, one can overall conclude that these two recent global financial crises did not significantly influence the mean returns.

However, 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 0.1378 (Australia) to a maximum of 0.2125 (the US). Significant positive cross-mean spillovers effects exist from the US to all three markets. We found that there is no positive and significant impact in the opposite direction. This impact is at its lowest for the UK (0.0911). The significant cross-mean spillovers impacting from the US to Singapore and to Australia are the same (0.1470). In addition, the Singapore market is also positively influenced by the UK returns. However, the impact from the UK (0.0945) is much lower than that of the US. In other words, the past US stock market returns exert greater impact on the Singapore stock market than the UK market returns. Table III also presents the R_i^2 values, which is calculated as $1-\left[\mathrm{var}(\varepsilon_{it})/\mathrm{var}(r_{iit})\right]$. 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 relatively low explanatory power due to the nature of high frequency financial data.

As an important finding, the coefficients of constant terms for both variance and covariance equations of each market are statistically significant. Furthermore, the estimated dummy variable coefficients for the Asian financial crisis in the variance equations are positive and significant for all four markets, suggesting that the Asian financial crisis had significant influence on the volatility of these four markets. This effect varies from 0.000014 (the US) to 0.000111 (Singapore). This indicates that the Asian crisis had the strongest impact on the Singapore market in terms of its rise in future volatility than the other three markets.

However, the dummy variable coefficients for the Asian crisis in covariance equations are insignificant for all four markets except for the covariance between Australia and the US (0.00001). This implies that the Asian financial crisis influenced own-volatility more than cross-market volatility. In other words, although the Asian financial crisis spread outside Asia during the end of 1998, it did not significantly impact on cross-market volatility among these four countries for the entire period (starting from the first week of July 1997 to the last week of September 1998). Most certainly, such impacts contributing to rising co-volatility have occurred for a much shorter period than the one proposed by the length of the sustained 1997 dummy variable.

The estimated coefficients for the dummy variables capturing the 2008 global financial crisis in the variance equations are positive and significant for all four markets. This suggests that the recent ongoing crisis sparked in 2008 increased the volatility of stock returns of Australia, Singapore, and the US. The lowest coefficient belongs to the UK (0.000118) and the highest to Singapore (0.000313). Furthermore, the dummy variable coefficients in our covariance equations are all positive and statistically significant, suggesting that the 2008 financial crisis has contributed to the rising covolatilities across these four markets. The lowest dummy coefficient in the covariance equation is between Australia and the UK (0.000094), while the highest figure occurs between Singapore and the US (0.000167). In addition, the dummy variable coefficient between the UK and Singapore (0.000145) in the covariance equation is higher than that of Australia. As expected, this indicates that the 2008 crisis had a higher impact on Singapore than Australia.

The spillovers in the second moments (i.e. volatility spillovers) indicate similarities in own-volatility spillovers but differences in cross-volatility spillovers in the context of the two crises. First, the own-volatility spillovers in these four stock markets increased during both financial crises. As identified by Schwert (1989, 1990), over-leveraging could have an influence on increasing own-volatility spillovers in each market during these two financial crises. Of note is that the own-volatility spillovers are greater in the recent global financial crisis compared to the Asian crisis. Apart from over-leveraging, a loss of confidence by investors in the value of sub-prime mortgages, a rise in defaults and under-provision for nonperforming loans by the banking system and the failure of banks to manage risks can also be regarded as other relevant causes of the volatility of stock markets during the recent global crisis. On the other hand, the dollarization of foreign debt could be another contributing factor for the increase in volatility of stock markets in the Asian crisis period.

Second, significant cross-volatility spillovers across all four markets do exist during the recent global financial crisis period only. Furthermore, the transmission of this volatility shocks during the recent financial crisis is the greatest from the US market to other markets. This particular finding is not counterintuitive, given the geographic dissimilarities of the origin of the two crises. The recent financial crisis emerged with the collapse of financial markets in the US, being the world's leading stock markets. As Sabri (2002) stated, the world's leading stock market would have an influence on the volatility of other markets. In addition, as Eun and Shim (1989, p254) argued "no national stock market is nearly as influential as the US in terms of its capability of accounting for the error variance of other markets." On the other hand, the Asian crisis originated with the collapse of Thai-baht leading to a disruption in foreign exchange markets mainly within the Asian region. This Asian financial turmoil occurred in Asian emerging economies, thus as expected it could not play a significant role on cross-volatility spillovers in stock markets outside the region.

Table III. Parameter estimation for the mean equation and the DVECH(1,1) specification

$$r_{iit} = \mu_{0i} + \delta_{97i} D_{97} + \delta_{08i} D_{08} + \sum_{j=1}^{4} \mu_{ij} r_{ijt-1} + \varepsilon_{it}$$

$$vech(H_t) = C + G^*_{97} D_{97} + G^*_{08} D_{08} + A^* vech(\varepsilon_{t-1}\varepsilon'_{t-1}) + B^* vech(H_{t-1})$$

Parameter	Australia		Singapore		UK		US	
	Coefficient	*t*-ratio	Coefficient	*t*-ratio	Coefficient	*t*-ratio	Coefficient	*t*-ratio
Parameter Estimation for Mean Equation								
μ_{0i}	0.001918***	4.68	0.001625**	2.78	0.001640***	3.33	0.001953***	4.31
δ_{97i}	-0.002637	-1.01	-0.009225*	-1.72	-0.000527	-0.18	0.001001	0.38
δ_{08i}	-0.005741	-0.97	-0.006333	-0.69	-0.007785	-1.16	-0.007856	-0.80
μ_{i1}	0.137761***	3.46	-0.029061	-0.57	-0.039055	-0.90	-0.093660**	-2.25
μ_{i2}	-0.011266	-0.49	0.181076***	5.24	-0.018691	-0.76	0.008681	0.36
μ_{i3}	0.011831	0.35	0.094490*	1.74	0.146963***	3.20	0.006885	0.16
μ_{i4}	0.146712***	3.81	0.146686**	2.65	0.091057**	2.02	0.212525***	4.64
Parameter Estimation for Variance Equation								
c_{i1}	0.000007**	2.94						
c_{i2}	0.000005**	2.59	0.000012**	3.02				
c_{i3}	0.000003**	2.55	0.000004**	2.66	0.000007***	3.20		
c_{i4}	0.000002**	2.72	0.000002**	2.45	0.000004***	3.24	0.000005***	3.50
g_{97i1}	0.000021**	2.22						
g_{97i2}	0.000028	1.52	0.000111**	2.32				
g_{97i3}	0.000009	1.62	0.000017	1.26	0.000018*	1.68		
g_{97i4}	0.000010*	1.78	0.000009	0.83	0.000010	1.42	0.000014*	1.91
g_{08i1}	0.000123**	1.97						
g_{08i2}	0.000180**	1.96	0.000313*	1.92				
g_{08i3}	0.000094*	1.88	0.000145**	2.01	0.000118*	1.73		
g_{08i4}	0.000118**	2.30	0.000167**	2.09	0.000138**	2.01	0.000194**	2.54
a_{i1}	0.062273***	4.23						
a_{i2}	0.040175***	3.45	0.083401***	5.01				
a_{i3}	0.040972***	4.31	0.033442***	3.46	0.053029***	5.53		
a_{i4}	0.039143***	4.75	0.031000***	3.53	0.042900***	5.73	0.051778***	5.44
b_{i1}	0.890255***	37.44						
b_{i2}	0.899079***	33.02	0.879960***	41.95				
b_{i3}	0.924573***	52.97	0.926846***	51.79	0.914996***	60.04		
b_{i4}	0.931266***	66.35	0.937198***	61.12	0.927191***	75.75	0.918589***	66.11
$a_{ii} + b_{ii}$	0.9525		0.9634		0.9680		0.9704	
R_i^2	0.0918		0.1008		0.0549		0.0491	

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}) point to the presence of ARCH effects in these four markets. This effect varies from 0.0518 (the US) to 0.0834 (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 the 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 our results, the degree of cross-volatility shocks is pair-wise the weakest between Singapore-the US (0.0310) and the strongest between the US-the UK (0.0429). We also found 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 0.0402, 0.0410, and 0.0391, respectively.

The estimated coefficients for the variance-covariance matrix (equation 3) have also been presented in Table III. The b_{ij} ($i = j$) coefficients for the one-lag conditional variance of all the 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 at its lowest in Singapore $\left(b_{22} = 0.8800\right)$ and the highest in the US market $\left(b_{44} = 0.9186\right)$. 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. The significant nonzero b_{ij} coefficients (where $i \neq j$ for all *i* and *j*) provide further evidence for high and positive volatility spillovers persistence across these well-integrated markets. The significant cross-volatility effects between Australia and those of Singapore, the UK, and the US are 0.8990, 0.9246, and 0.9313, respectively. This supports the evidence of volatility persistence emanating from all of the other three markets towards Australia. Furthermore, the cross-volatility persistence for Singapore, stemming from the UK and the US, are 0.9268 and 0.9372, respectively. In this respect, the most influential market would appear to be the US, which influences the Australian market more than that of Singapore. The sum of the lagged ARCH and GARCH coefficients ($a_{ii} + b_{ii}$) for Australia, Singapore, the UK and the US are 0.9525, 0.9634, 0.9680 and 0.9704 respectively. These values support the assumption of covariance stationarity and the volatility persistence in the data as they are very close to unity.

In addition to the results from our main model, i.e. equations (2) and (3), we have reported the diagnostic test results for the resulting standardized residual series. Table IV presents the normality test statistics, the unit root test results, and Ljung-Box test statistics for the standardised residual series of the model. The estimated result from these tests confirms that the resulting residuals are not normally distributed; all four standardised residual series are stationary and no serial correlation in the Australian and the US market. In addition, we also estimated the Portmanteau Box-Pierce/Ljung-Box Q-statistics and the adjusted Q-statistics for the standardised system residuals (see Table V). 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 providing further support for the DVECH model as it absorbs a great deal of inertia and ARCH and GARCH effects present in the original return series.

Table IV. Diagnostic tests on the standardized residuals of the model

	Australia		Singapore		UK		US	
Statistics on standardized residuals								
Skewness	-0.38		-0.11		0.14		-0.19	
Kurtosis	3.53		3.59		3.89		4.59	
Jarque-Bera	32.60		14.99		32.98		101.69	
ADF *t* statistics								
Based on min. AIC	-29.8098		-15.5269		-22.6024		-18.8140	
Based on min. SIC	-29.8098		-28.8456		-28.3060		-29.4805	
Ljung-Box test statistics for standardized residuals								
	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value
Q(1)	0.0815	0.78	1.6675	0.20	3.6758	0.06	0.4400	0.51
Q(2)	0.7560	0.69	6.9850	0.03	10.1800	0.01	0.9336	0.63
Q(3)	3.7334	0.29	9.3646	0.03	12.5950	0.01	5.3638	0.15
Q(4)	4.8164	0.31	10.8590	0.03	12.5970	0.01	5.5090	0.24
Q(5)	4.8166	0.44	10.9240	0.05	13.1130	0.02	7.5847	0.18
Q(6)	4.8593	0.56	10.9430	0.09	13.3120	0.04	7.7204	0.26
Q(7)	5.4871	0.60	11.0890	0.14	14.4790	0.04	7.7602	0.35
Q(8)	5.5590	0.70	11.1490	0.19	14.4810	0.07	7.8534	0.45
Q(9)	7.0983	0.63	11.2060	0.26	14.7800	0.10	7.9526	0.54
Q(10)	7.1067	0.72	11.4730	0.32	14.8690	0.14	8.6132	0.57
Q(11)	7.5568	0.75	11.4770	0.40	16.1570	0.14	8.9531	0.63
Q(12)	8.9771	0.71	11.4790	0.49	16.2130	0.18	9.5927	0.65
Q(13)	9.0695	0.77	11.6400	0.56	16.6370	0.22	11.2640	0.59
Q(14)	9.8075	0.78	11.6920	0.63	16.9020	0.26	11.3390	0.66
Q(15)	10.0170	0.82	11.9790	0.68	17.8080	0.27	12.7010	0.63
Q(16)	11.1320	0.80	13.6270	0.63	19.0530	0.27	12.8770	0.68
Q(17)	11.8760	0.81	16.2630	0.51	19.7910	0.29	13.4240	0.71
Q(18)	12.1220	0.84	16.2910	0.57	20.3310	0.31	14.9120	0.67
Q(19)	13.6330	0.81	16.5400	0.62	22.5480	0.26	14.9930	0.72
Q(20)	13.6700	0.85	17.0160	0.65	22.6120	0.31	15.1980	0.77
Q(21)	13.6910	0.88	17.1000	0.71	23.0840	0.34	16.3620	0.75
Q(22)	14.2630	0.89	17.3110	0.75	23.3450	0.38	16.3670	0.80
Q(23)	15.4350	0.88	18.9120	0.71	26.5810	0.27	16.4140	0.84
Q(24)	16.2090	0.88	19.0440	0.75	31.1620	0.15	16.7090	0.86

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

Table V. 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)	16.6173	0.41	16.6356	0.41	16
Q(2)	43.5499	0.08	43.6276	0.08	32
Q(3)	67.3428	0.03	67.4993	0.03	48
Q(4)	78.8653	0.10	79.0727	0.10	64
Q(5)	95.8372	0.11	96.1385	0.11	80
Q(6)	113.5867	0.11	114.0059	0.10	96
Q(7)	122.1900	0.24	122.6760	0.23	112
Q(8)	134.5419	0.33	135.1375	0.32	128
Q(9)	148.8275	0.37	149.5660	0.36	144
Q(10)	164.8283	0.38	165.7447	0.36	160
Q(11)	182.1975	0.36	183.3267	0.34	176
Q(12)	200.4630	0.32	201.8366	0.30	192
Q(13)	224.7974	0.20	226.5241	0.18	208
Q(14)	234.7163	0.30	236.5981	0.27	224
Q(15)	246.7989	0.37	248.8835	0.33	240
Q(16)	268.7214	0.28	271.1987	0.25	256
Q(17)	281.1721	0.34	283.8867	0.30	272
Q(18)	297.4716	0.34	300.5156	0.29	288
Q(19)	314.0194	0.33	317.4166	0.28	304
Q(20)	325.5034	0.40	329.1590	0.35	320
Q(21)	335.9299	0.49	339.8320	0.43	336
Q(22)	348.4701	0.54	352.6833	0.48	352
Q(23)	369.9371	0.46	374.7075	0.39	368
Q(24)	385.9889	0.46	391.1946	0.39	384

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

V SUMMARY AND CONCLUSION

This paper uses a multivariate DVECH model augmented with two dummy variables capturing the effects of the Asian financial crisis and the more recent global financial crisis to identify the source and magnitude of mean and volatility spillovers across these four markets. We have used a general vector stochastic process of assets returns and allowed the lagged returns of each country to influence the Australian market.

We could not find any positive significant influence on the mean returns in all four markets resulting from these two financial crises. However, our results indicate a significant influence arising from the Asian financial crisis on volatility in all four markets. We found that the Asian financial crisis influenced the own-volatility more than that of the cross-market volatility. One may argue that while during the entire 1997 crisis (i.e. from the first week of

July 1997 to the last week of September 1998) significant influences on co-volatility were not observed, however, the co-volatility across these four markets presumably did rise for a much shorter (country specific) period than the one proposed by the length of the sustained 1997 dummy variable utilised in this paper. The extent of individual influence from major events occurred during these financial crises on volatility transmission across these four markets have not been analysed in this study and further research requires on this issue.

Furthermore, our findings provide ample evidence that the 2008 financial crisis has contributed to the increased stock return volatilities across all these four markets. 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). Based on the magnitude of the own volatility shocks (own innovation effects), it is found that compared to Australia, the Singapore market is relatively more influenced by its own innovations. As expected, it is also found that the own and cross volatility persistence do exist among these four markets. In addition, Singapore and the US stock returns exhibit the lowest and highest magnitude of the own volatility persistence effect (the GARCH effect), respectively. This may tentatively suggest 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 when we move from larger markets to smaller markets. This could also suggest that in such small markets changes in volatility are more likely to emanate from cross volatilities intertwined within global financial markets.

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