

NCER Working Paper Series

Unobservable Shocks as Carriers of Contagion: A Dynamic Analysis Using Identified Structural GARCH

Mardi Dungey, George Milunovich and Susan Thorp

Working Paper #22

February 2008

Unobservable Shocks as Carriers of Contagion: A Dynamic Analysis Using Identified Structural GARCH*

Mardi Dungey[†], George Milunovich*, Susan Thorp[#]

[†]University of Cambridge

*Macquarie University

[#]University of Technology, Sydney

1 February 2008

Abstract

Markets in financial crisis may experience heightened sensitivity to news from abroad and they may also spread turbulence into foreign markets, creating contagion. We use a structural GARCH model to separate and measure these two parts of crisis transmission. Unobservable structural shocks are named and linked to source markets using variance decompositions, allowing clearer interpretation of impulse response functions. Applying this method to data from the Asian crisis, we find significant contagion from Hong Kong to nearby markets but little heightened sensitivity. Impulse response functions for an equally-weighted equity portfolio show the increasing dominance of Korean and Hong Kong shocks during the crisis, whereas Indonesia's influence shrinks.

Keywords: Contagion, Structural GARCH

JEL Classification: F37, C51

*We thank Andrea Cipollini, John Geweke, Tony Hall, Gordon Menzies, Adrian Pagan, Peter Phillips and participants at the 2007 INFINITI Conference, Trinity College Dublin, and seminar participants for helpful comments. Part of this paper was written while Thorp was a Visiting Scholar at Cambridge Endowment for Research in Finance, University of Cambridge.

I Introduction

Financial crises not only disrupt markets in the countries in which they occur, but often spread turmoil to otherwise well-functioning foreign markets. The existing literature generally labels this phenomenon as contagion.¹ In this paper we show that it is empirically possible to separate these increased crisis-period linkages between markets into two categories. The first category is heightened sensitivity to information from elsewhere during a local crisis, in other words, where domestic trouble makes a market more responsive to news from foreign markets. The second category is the increased impact of news from a market in crisis on other (potentially non-crisis) markets - we reserve the label ‘contagion’ for this second effect. These categories can be separately measured whenever domestic and foreign crises are not totally coincident.²

This distinction is not an unnecessary abstraction, instead, each category suggests different potential policy reactions to managing and preventing crises. While the policy makers of a country in crisis are likely to be interested in preventing heightened sensitivity, that is preventing their own troubled market from becoming more sensitive to external news, they have little incentive to prevent contagion to external markets. On the other hand, a crisis may generate an externality to other countries in the form of contagion, and governments of non-crisis countries may want to protect their markets from foreign contagion if possible. The existence of these externalities is consistent with the agenda for coordinated global reforms in regulation, financial infrastructure and instrument design following major incidents (see, for example, Mishkin (1998) on Latin America, Eichengreen (2002) on East Asia and Alexander, Eatwell, Persuad and Reoch (2007) on the sub-prime crisis).

Here we model the concepts of heightened sensitivity and contagion while capturing the characteristics of daily financial market data by constructing a multivariate GARCH model of asset market interaction, where different regimes represent exogenously-identified crisis periods. The regimes capture any changed volatilities in returns during tranquil and crisis periods. We use identification by heteroskedasticity to estimate structural parameters, thus extending the work of Caporale et al. (2005) and Rigobon and Sack (2004).

We also propose an innovative approach to classifying and interpreting structural shocks by attributing them to a specific source market using variance decompositions. Unlike previous approaches, this method is data-driven and does not rely on arbitrary restrictions such as market hierarchies. Further, the richness of the interactions in our model contributes to

the developing empirical literature on cross country and cross asset market crisis models (Dungey and Martin 2007; Hartmann, Straetmans and de Vries 2004) and the move away from modelling contagion via correlation.

Taking the perspective of a risk-averse international investor, we model daily U.S. dollar returns in major equity market indices during the complex series of interrelated crises in Asia over the period 1997-1998. The sample consists of Hong Kong, Indonesia, Korea and Thailand, each of which had their own crises and potentially also received transmissions from other crisis countries. The results show statistically significant contagion between a number of countries but, in most cases, the evidence for heightened sensitivity is not significant. Innovation accounting using an equally-weighted portfolio of equity price indices show the rise in importance of the Hong Kong-sourced shocks during the crisis. On the other hand, foreign markets seemed to have been shielded from shocks originating in Indonesia during the crisis there.

In Section II we set out the modelling strategy and Section III explains the dynamic analysis. The Asian data and estimation results are reported in Sections IV and V. Section VI concludes.

II Modelling Strategy

Consider a vector of k de-meaned asset returns \mathbf{Y}_t that are all potentially contemporaneously interlinked in non-crisis periods, so that the system can be described as³

$$\mathbf{B}^* \mathbf{Y}_t = \mathbf{u}_t \tag{1}$$

where \mathbf{B}^* is a $k \times k$ matrix of coefficients representing these non-crisis linkages, b_{ij} , normalized on the diagonal elements of \mathbf{B}^* . The $k \times 1$ vector \mathbf{u}_t represents the idiosyncratic shocks in the system,

$$\mathbf{u}_t = \mathbf{g}_t \boldsymbol{\varepsilon}_t \tag{2}$$

$$\varepsilon_{it} \sim iidN(0, 1) \tag{3}$$

where \mathbf{g}_t is a $k \times k$ diagonal matrix. (Scaled structural innovations \mathbf{u}_t are independent.) The underlying shocks themselves, given by $k \times 1$ vector $\boldsymbol{\varepsilon}_t$, are distributed *i.i.d.* standard normal. Appendix A gives a detailed $k = 2$ dimensional example of the model and dynamics.

Here, heightened sensitivity or contagion is captured by a change in the strength of linkages between asset returns during a crisis, consistent with the approach of Forbes and Rigobon (2002), Favero and Giavazzi (2002), Pesaran and Pick (2007) amongst others. The model explicitly recognizes that countries are receivers of contagion effects from abroad, and also that during periods of domestic crisis, home markets may become super-sensitive to foreign shocks. In the past, these two effects have not been separately distinguished nor empirically quantified, both being captured in a single measure. Consider a model that includes both tranquil and crisis periods as follows:

$$\mathbf{B}\mathbf{Y}_t = \mathbf{u}_t, \text{ where } \mathbf{B} := (\mathbf{B}^* + \mathbf{B}_{c,s}\mathbf{D}_t), \quad (4)$$

with $\mathbf{B}_{c,s}\mathbf{D}_t$ representing the linkages present in crisis periods. *Contagion* (indicated by subscript c) is modelled as the additional impact on the asset market in home country i during a crisis in foreign country j , given by the parameters $b_{c,ij}$ in each equation. *Heightened sensitivity* (indicated by subscript s), is given by the parameter $b_{s,ij}$ in each equation measuring the additional impact of foreign shocks during a domestic crisis. Each period of crisis is identified using an indicator variable $D_{i,t}$ which is one during the crisis in home country i and zero otherwise. The relevance of each instance of contagion and heightened sensitivity is tested by the significance of the parameters $b_{c,ij}$ and $b_{s,ij}$. In the case of no contagion or heightened sensitivity in the system $b_{c,ij} = b_{s,ij} = 0$ for all i, j .

We model the known fat-tailed characteristics of the financial markets returns in \mathbf{Y}_t . Given the structure of (2) to (4) it is straightforward to see that

$$\mathbf{B}\mathbf{Y}_t \sim (0, E[\mathbf{G}_t]),$$

where $\mathbf{G}_t = \mathbf{g}_t\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}_t'\mathbf{g}_t'$ is a $k \times k$ diagonal matrix of the squares of the elements of the matrix \mathbf{g}_t .

The conditional covariance matrix of the structural shocks is a GARCH(1,1), specified for \mathbf{G}_t as

$$\mathbf{G}_t = \text{diag}[\boldsymbol{\psi} + \boldsymbol{\lambda}(\mathbf{u}_{t-1} \circ \mathbf{u}_{t-1})] + \boldsymbol{\zeta}\mathbf{G}_{t-1}, \quad (5)$$

where $\boldsymbol{\psi}$ is a $k \times 1$ vector of constants, $\boldsymbol{\psi}_i$, $\boldsymbol{\lambda}$ is a $k \times k$ diagonal matrix of ARCH coefficients and $\boldsymbol{\zeta}$ is a $k \times k$ diagonal matrix of GARCH coefficients.

Since both \mathbf{G}_{t-1} and \mathbf{u}_{t-1} are unobservable, we specify the system as a reduced form.

$$\mathbf{Y}_t = \boldsymbol{\kappa}_t, \text{ where } \boldsymbol{\kappa}_t := \mathbf{B}^{-1}\mathbf{u}_t. \quad (6)$$

The joint conditional distribution of the vector of de-meaned returns is

$$\mathbf{Y}_t \sim (0, \mathbf{H}_t), \quad (7)$$

and we work with this reduced form covariance matrix, \mathbf{H}_t , which can be estimated as a multivariate GARCH process in the de-meaned returns vector \mathbf{Y}_t , $\mathbf{H}_t = \mathbf{A}\mathbf{G}_t\mathbf{A}'$, where $\mathbf{A} := \mathbf{B}^{-1}$.

Identification of the structural parameters in \mathbf{B} from the estimated value of \mathbf{H}_t depends on establishing the link between the structural parameters and the reduced form. The lower diagonal elements of the reduced form covariance matrix \mathbf{H}_t can be expressed as ⁴

$$vech(\mathbf{H}_t) = \mathbf{C}_0 + \mathbf{C}_1(\boldsymbol{\kappa}_{t-1} \circ \boldsymbol{\kappa}_{t-1}) + \mathbf{C}_2\mathbf{h}_{t-1} \quad (8)$$

where \mathbf{C}_0 is a $k(k+1)/2 \times 1$ vector of constant coefficients, \mathbf{C}_1 is a $k(k+1)/2 \times k$ matrix of ARCH coefficients, \mathbf{C}_2 is a $k(k+1)/2 \times k$ matrix of GARCH coefficients and \mathbf{h}_t is a $k \times 1$ vector of the diagonal elements of \mathbf{H}_t .

To establish the relationship between the coefficients of \mathbf{H}_t and the structural parameters we begin with the vector of ARCH terms. Relying on the independence of structural shocks, we set cross products to zero, and write

$$(\mathbf{A} \circ \mathbf{A})^{-1} \boldsymbol{\kappa}_{t-1} \circ \boldsymbol{\kappa}_{t-1} = (\mathbf{u}_{t-1} \circ \mathbf{u}_{t-1}). \quad (9)$$

Next we can make a similar transformation of the GARCH terms:

$$(\mathbf{A} \circ \mathbf{A})^{-1} \mathbf{h}_{t-1} = vech(\mathbf{G}_{t-1}), \quad (10)$$

where $vecd$ is the vector of the diagonal elements of the matrix.

If we again rewrite $\mathbf{H}_t = \mathbf{A}\mathbf{G}_t\mathbf{A}'$ in $vech(\cdot)$ form and define the required transformation of the \mathbf{A} matrix as \mathbf{A}^v , a $k(k+1)/2 \times k$ matrix of products of the elements of \mathbf{A} , then the reduced form covariance matrix is comprised of structural shocks and structural parameters,

$$vech(\mathbf{H}_t) = \mathbf{A}^v\boldsymbol{\psi} + \mathbf{A}^v\boldsymbol{\lambda}(\mathbf{u}_{t-1} \circ \mathbf{u}_{t-1}) + \mathbf{A}^v\boldsymbol{\zeta}vecd(\mathbf{G}_{t-1}). \quad (11)$$

Finally by substituting equation (9) and equation (10) we can link the \mathbf{C} matrices of the reduced-form MGARCH and the structural parameters,

$$vech(\mathbf{H}_t) = \mathbf{A}^v\boldsymbol{\psi} + \mathbf{A}^v\boldsymbol{\lambda}(\mathbf{A} \circ \mathbf{A})^{-1}(\boldsymbol{\kappa}_{t-1} \circ \boldsymbol{\kappa}_{t-1}) + \mathbf{A}^v\boldsymbol{\zeta}(\mathbf{A} \circ \mathbf{A})^{-1}\mathbf{h}_{t-1}. \quad (12)$$

Estimation and identification of structural form parameters therefore depends on the estimation of the reduced form covariance matrix expressed in terms of structural parameters. The coefficients from the reduced form in equation (8) provide $k(k + 1)/2$ parameters in the \mathbf{C}_0 matrix, $k^2(k + 1)/2$ parameters in each of the \mathbf{C}_1 and \mathbf{C}_2 matrices for a total of $(2k + 1)(k + 1)k/2$. The structural model contains $3k(k - 1)$ parameters in the \mathbf{B} matrix and $3k$ GARCH parameters for a total of $3k^2$. (In the four-country example estimated below there are 48 structural parameters and 90 reduced form parameters.)

Structural parameters are non-linear transformation of the reduced form parameters in the model, so an analytical proof of identification is difficult. Rothenberg (1971, Theorem 7) shows that for non-linear systems of equations, under weak regularity conditions, an ‘overly strong sufficiency condition’ for global identification of structural parameters is met when the Jacobian matrix of second order partial derivatives with respect to the structural parameters has a positive determinant. While we do not prove this condition analytically, we can offer numerical evidence for identification of the specific model and dataset discussed here: we consistently achieve convergence in the maximization of the structural likelihood function from a range of starting values. We also check the numerical identification and optimization procedure by estimating from simulated data.

III Dynamics

Innovation accounting within the SGARCH model gives a mapping of the dynamics of transmissions between markets. Making tranquil period dynamics the benchmark, we can examine the dynamics of both contagion and heightened sensitivity effects during periods of crisis. We take the position of an international investor holding an equally weighted portfolio of each of the market indices in the model, and track the impact of structural impulses on the volatility of this naive benchmark portfolio. While this is a convenient application of the processes and effects, the potential for exploring the dynamics in this model are much wider than this example. The model can be used to track individual transmission paths for shocks from all domestic and foreign sources under each of the four crises in the sample, separating heightened sensitivity and contagion effects.⁵

The structural shocks are connected to their source market using variance decompositions: the shocks which contribute the largest part of domestic-market forecast error variance during the tranquil period are labelled the domestic-market shocks. We do not need to use arbitrary

restrictions to name the shocks. This tranquil period classification lets us trace the sources of turbulence during crises back to a specific country.

The 1–step ahead conditional forecast error variance for \mathbf{Y}_t is simply the fitted values of the reduced form conditional covariance matrix:

$$\begin{aligned} \text{var}_t [\mathbf{Y}_{t+1} - E_t(\mathbf{Y}_{t+1})] &= \text{var}_t [\mathbf{B}^{-1}\mathbf{u}_{t+1} - E_t(\mathbf{B}^{-1}\mathbf{u}_{t+1})] \\ &= \mathbf{H}_{t+1|t}, \end{aligned}$$

if all estimated parameter values are assumed known with certainty.

The conditionally heteroskedastic properties of the model mean that forecast errors vary with realized volatility at time t , effectively providing a distribution of forecast error variances based, as it were, on a series of random draws from the structural error distributions. Such a distribution allows us to infer empirical quantiles for the forecast error variance and its decompositions. The forecast error variance is a non-linear function of structural parameters and structural shocks, however the identification of structural parameters during estimation means that it is possible to numerically identify the structural errors via the relationship $\mathbf{B}\mathbf{Y}_t = \mathbf{g}_t\boldsymbol{\varepsilon}_t$ so that $\mathbf{g}_t^{-1}\mathbf{B}\mathbf{Y}_t = \boldsymbol{\varepsilon}_t$.

The percentage of the forecast error variance $VD_{i,j}$, for y_i that is due to each structural error ε_j is computed as

$$VD_{i,j} = \frac{\left(\mathbf{A}\mathbf{g}_{j,t+1|t}\mathbf{g}'_{j,t+1|t}\mathbf{A}'\right)_{ii}}{\left(\mathbf{A}\mathbf{g}_{t+1|t}\mathbf{g}'_{t+1|t}\mathbf{A}'\right)_{ii}} \times 100, \quad (13)$$

where $\mathbf{g}_{j,t+1|t}$ is the j th column of the 1–period ahead forecast standard deviation matrix $\mathbf{g}_{t+1|t}$.

In the event that an investor holds an equally-weighted portfolio across the k markets, the forecast error variance decomposition for the portfolio indicates the shift in portfolio risk associated with exposure to a particular market during a crisis. In this case it is also necessary to include the effects of the interaction of shocks within the portfolio and the effects of diversification on reducing overall portfolio risk. The proportion of portfolio volatility associated with each structural shock component can be computed as

$$VD_{p,j} = \frac{w'\mathbf{A}\mathbf{g}_{j,t+1|t}\mathbf{g}'_{j,t+1|t}\mathbf{A}'w}{w'\mathbf{A}\mathbf{g}_{t+1|t}\mathbf{g}'_{t+1|t}\mathbf{A}'w} \times 100 \quad (14)$$

where w is a $k \times 1$ vector of portfolio weights, in our example, the unit vector. Using 14 we

can compare the mean contribution of each shock to portfolio variance during the tranquil and crisis periods.

Conditional impulse responses for the variance of the individual returns can be computed using the approach of Lin (1997). For the equally-weighted portfolio the response is the expectation at time t of the partial derivative of $\mathbf{w}'\mathbf{H}_{t+n}\mathbf{w}$ with respect to $\partial\varepsilon_{j,t}^2$, given by

$$E_t \left[\frac{\partial \mathbf{w}'\mathbf{H}_{t+n|t}\mathbf{w}}{\partial \varepsilon_{j,t}^2} \right] = E_t \left[\frac{\partial \mathbf{w}'\mathbf{A}\mathbf{G}_{t+n|t}\mathbf{A}'\mathbf{w}}{\partial \varepsilon_{j,t}^2} \right]. \quad (15)$$

IV The Asian Crisis

The Asian crisis of 1997-1998 exemplified the complexities which can arise between financial markets. There were multiple crises in a number of countries in the region, and across several different classes of assets. The debate over the causes of, and links between, these crises remains unresolved.

The discursive literature at the time of the Asian crisis viewed pressure in the Hong Kong equity market around October 1997 as leading to pressure on equity markets in other countries, and particularly in precipitating crisis in Korean markets. Four of the major countries involved in the turmoil during 1997-1998 were Thailand, Indonesia, Korea and Hong Kong. However empirical evidence on contagion during this period is mixed. On one hand, Forbes and Rigobon (2002) and Kleimeier, Lehnert and Verschoor (2003) find little evidence for contagion in these equity markets using bivariate correlation tests. On the other hand, each of Baig and Goldfajn (1999), Caporale, Cipollini and Spagnolo (2003) and Baur and Schulze (2005) find statistically significant contagion effects.⁶

Returns are constructed as the residuals from a VAR(1) on the log changes in the daily US dollar-valued equity market indices for each country, including also the change in the 3-month U.S. Treasury Bill rate as a proxy for an exogenous common shock, following Forbes and Rigobon (2002).⁷ Figures 1 to 4 show the time series of returns.

The model proposed in Section II requires an exogenous identification of the indicator variables, D_i for $i = 1, \dots, k$, where k is the total number of assets involved. The crisis dates for each individual country are collated from existing sources. The Hong Kong crisis period is set as 27 October 1997 to 17 November 1997 (Billio and Pelizzon, 2003; Rigobon, 2003). The Indonesian crisis period is set as 1 January 1998 to 27 February 1998 encompassing the period of high volatility in returns associated with political uncertainty and IMF negotiations.

The Korean crisis occurs in the lead up to successful renegotiation of its debt moratorium with the IMF on 24th December. Clearly (Panel C in Figure 1) the volatility in this market began in late November; we designate the Korean crisis period from 25 November 1997 to 31 December 1997. The Thai crisis in equity markets dates from 10 June 1997 to 29 August 1997 (Billio and Pelizzon, 2003; Rigobon, 2003). The crisis periods are shown as the narrow shaded areas in each of the panels of Figure 1.

[INSERT FIGURE 1 HERE]

Table 1 gives some descriptive statistics for the returns series. The first panel is for the entire sample. The following four panels give the crisis periods chronologically. The table shows that in general the volatility of returns rises when a market is in crisis.

[INSERT TABLE 1 HERE]

V Estimation Results

The results of applying the model of Section II to the Asian dataset are given in Table 2. Estimation was performed using quasi-maximum likelihood techniques (QML) via numerical methods in Ox. The tranquil period coefficient estimates are shown in the top panel of Table 2. There are significant linkages between a number of the equity markets. The Hong Kong market exhibits a significant positive relationship with returns in Indonesia and Korea while the Korean returns are positively related to Indonesia during periods of tranquility. The Indonesian market is also significantly affected by Hong Kong and Korea. The Thai market appears to import a positive impact from all three neighbors in the tranquil period, but does not influence the other markets.

[INSERT TABLE 2 HERE]

Contagion occurs when the country in question is affected by a crisis in other countries. The strength of these effects are shown in the second panel in Table 2. Indonesia experienced contagion from the Hong Kong and Korean crises. During the Hong Kong crisis, the Korean market sensitivity to shocks from Hong Kong increased substantially by 0.645 over the tranquil measure of -0.125. There is also an additional negative covariance between Thai and Hong Kong returns during the Hong Kong crisis.

The negative coefficient represents an interesting addition to the literature, in that it suggests that during periods of crisis, links between two markets are sometimes weaker rather than stronger. This is consistent with Forbes and Rigobon (2002) who find a fall in conditional correlation in many instances.

Heightened sensitivity occurs when the connection between domestic markets and foreign markets changes during a domestic crisis period. Results are shown in the third panel of Table 2. Here only one linkage is statistically significant and is also negative, indicating that Korean returns covaried negatively with Indonesian returns during the Korean crisis.

Table 3 provides the parameter estimates for the GARCH behavior of the underlying shocks. In each of the cases there is a small positive and significant constant and significant ARCH and GARCH effects. The combined ARCH and GARCH parameters sum close to one in each case.

[INSERT TABLE 3 HERE]

In summary we find evidence for shifts in the relationships between the equity markets of Hong Kong, Indonesia, Korea and Thailand during the crisis period, but these effects are not uniform in direction or significance across countries and crises. In terms of strengthening effects, the Hong Kong crisis had a large impact on regional markets, generating significant contagion in Indonesia and Korea but creating a weakening link with Thailand, where correlation fell. Similarly, Korean links with Indonesia became significantly weaker during Korea's own crisis, but otherwise heightened sensitivity did not appear to change links with other external markets. Overall we find evidence of significant contagion, but less of heightened sensitivity.

A Variance Decomposition

The first panel of Table 4 gives the tranquil period decomposition at one step ahead, with 5th and 95th quantile measures.⁸ These results are used to allocate the shocks to their source market. In each case, we label the shock that makes the greatest contribution to volatility in each of the tranquil-period decompositions as the own-country shock.⁹ These contribute at least 80% of forecast error variance in each case. The maximum impact from another country at the mean is 16% (the link from Korean shocks to the Hong Kong market). The final column in Table 4 gives the variance decompositions for the equally weighted portfolio,

which also account for covariance between the returns. In the tranquil period Korean and Indonesian shocks are dominant, at 39% and 31% of the total whereas Hong Kong and Thailand contribute around 15% each.

[INSERT TABLE 4 HERE]

The variance decompositions relating to links due to heightened sensitivity during crisis periods are shown in the second panel of Table 4.¹⁰ The only decomposition which changes substantially from that in the tranquil period is for Korea, where the contribution of domestic shocks is diminished by approximately 20 percentage points and the impact of Indonesia increases commensurately. The portfolio results show an increase of 17 percentage points from Korea (56%), 14 percentage points from Thailand (21%) and a small increase from Hong Kong. The contribution from Indonesia is reduced, most likely due to the changing link between Indonesia and Korea.

However the links due to contagion change more dramatically. The third panel of Table 4 shows that the contribution of domestic market shocks to the one-step-ahead variance decomposition is greatly reduced under foreign crises compared with the tranquil period. Change is most dramatic for Indonesia where the contribution from domestic shocks drops by 70 percentage points to a mean contribution of 28%; contagion from Korea (43%) and Hong Kong (28%) account for this. The contribution of the domestic shock for Hong Kong falls by about 10 percentage points to 70% in favour of an increase in Korean contribution to 26%. The contribution of domestic shocks for Korea decreases by about 20 percentage points, and the influence of Hong Kong rises from less than 1% to almost 20%. There is no real change in the Thai decomposition. Hence, Hong Kong shocks are clearly important in all countries apart from Thailand. This is also evident in the portfolio results, where the contribution of Hong Kong increases by 16 percentage points to 32% and the Korean contribution increases to 52% due to contagion effects. However, there are falls in the percentage contributions of Indonesia and Thailand to portfolio variance.

B Impulse Response Functions

Figure 2 presents impulse responses in the variance of the equally weighted portfolio to one standard deviation shocks from Hong Kong, Indonesia, Korea and Thailand respectively. The left column shows the impulse response in the tranquil period, and the right column shows

the responses with contagion effects. Using the unconditional (sample) portfolio variance as a basis for calculation, a 0.1 increase in portfolio variance is approximately equal to a 0.6 percentage point increase in annualised portfolio volatility.

[INSERT FIGURE 2 HERE]

A structural shock associated with Hong Kong in the tranquil period is the smallest of those investigated here, and takes about two months to dissipate half the initial impact. When we account for contagion, however, the effect of a one standard deviation shock is to raise variance by a factor of 10 over the tranquil period, with increases persisting above the tranquil level for well over six months.

Patterns for impulses to structural shocks from Indonesia are remarkably different. The initial impact of a one standard deviation shock in the tranquil period is very large and the distribution of responses is also very dispersed. By contrast, contagion effects are small in this case, so that unlike Hong Kong, impulse responses for shocks from Indonesia in tranquil and contagion periods are very alike.

The impact of Korean shocks in the tranquil period is greater than for Hong Kong, but not so large as for the Indonesian case already discussed. During the tranquil period there are statistically significant linkages with all the other countries in the sample, as shown in Table 2. The contagion effects are substantial, with the size of the initial shock in the external crisis scenario being six-fold the tranquil period shock, necessitating a differing scale on this panel to the other panels in the figure. Half of this impact has dissipated by 47 days after the shock, but some effect is still present nearly a year after the initial shock.

As a result of the lack of linkages from Thailand to other markets, the impulse responses to shocks originating from Thailand are the same in each of the tranquil and contagion periods.

VI Conclusion

Our analysis sets out an important refinement to the taxonomy of crises: we distinguish between heightened sensitivity and contagion. A local market may experience contagion as the recipient of an increase in pre-existing links with, or via the opening of a new channel of transmission from, a foreign market in distress, and a local market may also experience heightened sensitivity to shocks from foreign markets, during a domestic market crisis.

Contagion and heightened sensitivity map into policy discussions of crisis prevention and management, in the sense that policies need to be incentive compatible with the actively operating links.

Here we analyze heightened sensitivity and contagion in a multivariate GARCH model which allows for possible switching in transmission channels during exogenously defined crisis periods. Structural parameters can be identified from the reduced form. Unlike past work, which has relied on arbitrary restrictions to classify the sources of unobservable structural shocks, we use variance decompositions to label the structural shocks and connect them to source markets. This approach enables an economically justifiable interpretation of risk transmission in tranquil and crisis periods.

Applying this model to four Asian equity markets during the East Asian crisis period of 1998-1999, we observe statistically significant contagion links, but little in the way of heightened sensitivity. We show the changes in portfolio volatility for an equally-weighted portfolio of the four equity assets due to shocks originating in each country during both tranquil and crisis periods. In particular, while the dominant role of Korean shocks is amplified in the move from tranquility to crisis, the influence of shocks from Indonesia shrinks dramatically, whereas the impact of Hong Kong-sourced shocks increases.

Appendix A: Two-Asset Illustration

Here we present a two-dimensional illustration of the main features of the model and dynamics.

The tranquil period model for de-meaned returns for asset markets 1 and 2 is:

$$y_{1t} = b_{12}y_{2t} + g_{11,t}\varepsilon_{1t} \quad (16)$$

$$y_{2t} = b_{21}y_{1t} + g_{22,t}\varepsilon_{2t}, \quad (17)$$

which can be extended for crisis periods to

$$y_{1t} = b_{12}y_{2t} + b_{s,12}D_{1t}y_{2t} + b_{c,12}D_{2t}y_{2t} + g_{11,t}\varepsilon_{1t}$$

$$y_{2t} = b_{21}y_{1t} + b_{s,21}D_{2t}y_{1t} + b_{c,21}D_{1t}y_{1t} + g_{22,t}\varepsilon_{2t},$$

where the binary dummy variables, D_{1t} and D_{2t} take the value 1 during periods of crisis experienced in y_{1t} and y_{2t} respectively, and 0 otherwise. For the rest of the example, we work with the simpler tranquil period model. The matrix of contemporaneous market linkages is normalized on the diagonal to give,

$$\mathbf{B} = \begin{bmatrix} 1 & -b_{12} \\ -b_{21} & 1 \end{bmatrix}$$

and

$$\mathbf{B}^{-1} := \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}.$$

The GARCH processes on ε_i in this case are:

$$\begin{aligned} \begin{bmatrix} g_{11t}^2 & 0 \\ 0 & g_{22t}^2 \end{bmatrix} &= \text{diag} \left\{ \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} + \begin{bmatrix} \lambda_{11} & 0 \\ 0 & \lambda_{22} \end{bmatrix} \begin{bmatrix} u_{1t-1}^2 \\ u_{2t-1}^2 \end{bmatrix} \right\} \\ &+ \begin{bmatrix} \zeta_{11} & 0 \\ 0 & \zeta_{22} \end{bmatrix} \begin{bmatrix} g_{11t-1}^2 & 0 \\ 0 & g_{22t-1}^2 \end{bmatrix}. \end{aligned}$$

so that $g_{ii,t}\varepsilon_{it} = u_{it}$.

To estimate the simple model structure in (16) and (17) we need to account for the covariance between y_{it} and u_{jt} and the identification of structural parameters, and we resolve both estimation issues by working with the reduced-form covariance matrix.

For two assets, the reduced form covariance matrix $\text{vech}\mathbf{H}_t = \mathbf{A}^v \text{vecd}(\mathbf{G}_t)$ from equation (8) can be expressed as

$$\begin{bmatrix} H_{11,t} \\ H_{21,t} \\ H_{22,t} \end{bmatrix} = \begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{11}a_{21} & a_{12}a_{22} \\ a_{21}^2 & a_{22}^2 \end{bmatrix} \times \left\{ \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} + \begin{bmatrix} \lambda_{11}u_{1t-1}^2 \\ \lambda_{22}u_{2t-1}^2 \end{bmatrix} + \begin{bmatrix} \zeta_{11}g_{11t-1}^2 \\ \zeta_{22}g_{22t-1}^2 \end{bmatrix} \right\}$$

From (9) above we can write

$$\begin{aligned}
\boldsymbol{\kappa}_{t-1} \circ \boldsymbol{\kappa}_{t-1} &= \mathbf{A}\mathbf{u}_{t-1} \circ \mathbf{A}\mathbf{u}_{t-1} \\
&= \begin{bmatrix} (a_{11}u_{1t-1} + a_{12}u_{2t-1})^2 \\ (a_{21}u_{1t-1} + a_{22}u_{2t-1})^2 \end{bmatrix} \\
\begin{bmatrix} \kappa_{1t-1}^2 \\ \kappa_{2t-1}^2 \end{bmatrix} &= \begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{21}^2 & a_{22}^2 \end{bmatrix} \begin{bmatrix} u_{1t-1}^2 \\ u_{2t-1}^2 \end{bmatrix} \\
\begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{21}^2 & a_{22}^2 \end{bmatrix}^{-1} \begin{bmatrix} \kappa_{1t-1}^2 \\ \kappa_{2t-1}^2 \end{bmatrix} &= \begin{bmatrix} u_{1t-1}^2 \\ u_{2t-1}^2 \end{bmatrix}
\end{aligned}$$

using the assumption that the structural shocks are independent so that cross products in u_{1t} and u_{2t} can be set to zero. From equation (10)

$$\begin{aligned}
\mathbf{h}_{t-1} &= \begin{bmatrix} H_{11t-1} \\ H_{22t-1} \end{bmatrix} = \begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{21}^2 & a_{22}^2 \end{bmatrix} \begin{bmatrix} g_{11t-1}^2 \\ g_{22t-1}^2 \end{bmatrix} \\
\begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{21}^2 & a_{22}^2 \end{bmatrix}^{-1} \begin{bmatrix} H_{11t-1} \\ H_{22t-1} \end{bmatrix} &= \begin{bmatrix} g_{11t-1}^2 \\ g_{22t-1}^2 \end{bmatrix}
\end{aligned}$$

If we rewrite \mathbf{H}_t in $vech(\cdot)$ form and define the requisite transformation of the \mathbf{A} matrix as \mathbf{A}^v then

$$\begin{bmatrix} H_{11,t} \\ H_{21,t} \\ H_{22,t} \end{bmatrix} = \begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{11}a_{21} & a_{12}a_{22} \\ a_{21}^2 & a_{22}^2 \end{bmatrix} \left\{ \begin{array}{l} \begin{bmatrix} \psi_1 \\ \psi_2 \end{bmatrix} + \begin{bmatrix} \lambda_{11} & 0 \\ 0 & \lambda_{22} \end{bmatrix} \begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{21}^2 & a_{22}^2 \end{bmatrix}^{-1} \begin{bmatrix} \kappa_{1t-1}^2 \\ \kappa_{2t-1}^2 \end{bmatrix} \\ + \begin{bmatrix} \zeta_{11} & 0 \\ 0 & \zeta_{22} \end{bmatrix} \begin{bmatrix} a_{11}^2 & a_{12}^2 \\ a_{21}^2 & a_{22}^2 \end{bmatrix}^{-1} \begin{bmatrix} H_{11t-1} \\ H_{22t-1} \end{bmatrix} \end{array} \right\}$$

Dynamics

The proportion of the forecast error variance for return to domestic market one, y_1 , that is due to structural shock ε_1 is

$$VD_{1,1} = \frac{a_{11}^2 g_{1,t+1|t}^2}{a_{11}^2 g_{1,t+1|t}^2 + a_{12}^2 g_{2,t+1|t}^2}$$

and due to structural shock ε_2 is

$$VD_{1,2} = \frac{a_{22}^2 g_{2,t+1|t}^2}{a_{11}^2 g_{1,t+1|t}^2 + a_{12}^2 g_{2,t+1|t}^2}$$

The proportion of portfolio error variance for an equally weighted portfolio ($w = 1/k$) includes the impact of diversification, and error sourced in ε_1 would be represented by the following expression,

$$\begin{aligned}
VD_{p,1} &= [g_{1,t+1|t}^2 (a_{11}^2 + a_{12}a_{11} + a_{21}a_{11} + a_{21}a_{12})] / \\
&\quad [g_{1,t+1|t}^2 (a_{11}^2 + a_{12}a_{11} + a_{21}a_{11} + a_{21}^2) + g_{2,t+1|t}^2 (a_{12}^2 + a_{12}a_{22} + a_{12}a_{22} + a_{22}^2)].
\end{aligned}$$

Impulse responses in this case are

$$\begin{aligned}
E_t \left[\frac{\partial \mathbf{w}' \mathbf{H}_{t+1} \mathbf{w}}{\partial \varepsilon_{1,t}^2} \right] &= \partial \left[\left(\frac{1}{2} \right)^2 \left[\begin{array}{c} g_{1,t+1|t}^2 (a_{11}^2 + a_{12}a_{11} + a_{21}a_{11} + a_{21}^2) \\ + g_{2,t+1|t}^2 (a_{12}^2 + a_{12}a_{22} + a_{12}a_{22} + a_{22}^2) \end{array} \right] \right] / \partial \varepsilon_{1,t}^2 \\
&= (1/2)^2 (a_{11}^2 + a_{12}a_{11} + a_{21}a_{11} + a_{21}^2) \frac{\partial g_{1,t+1|t}^2}{\partial \varepsilon_{1,t}^2}
\end{aligned}$$

which creates a recursion in the structural parameters so that for an initial shock $\varepsilon_{1,t}^2 = 1$ in period t ,

$$\begin{aligned}
g_{1,t+1|t}^2 &= \psi_1 + \lambda_1 u_{1,t}^2 + \zeta_1 g_{1,t}^2 \\
\frac{\partial g_{1,t+1|t}^2}{\partial \varepsilon_{1,t}^2} &= \lambda_1 g_{1,t}^2
\end{aligned}$$

and

$$E_t \left[\frac{\partial \mathbf{w}' \mathbf{H}_{t+1} \mathbf{w}}{\partial \varepsilon_{1,t}^2} \right] = (1/2)^2 (a_{11}^2 + a_{12}a_{11} + a_{21}a_{11} + a_{21}^2) \lambda_1 g_{1,t}^2.$$

References

- Alexander, Kern, John Eatwell, Avinash Persaud and Robert Reoch, "Financial Supervision and Crisis Management in the EU", EU Policy Department Economic and Scientific Policy Document IP/A/ECON/IC/2007-069 (2007).
- Allen, Franklin and Douglas Gale, "Financial Contagion", *Journal of Political Economy* 108:1 (2000), 1-33.
- Baig, Taimur and Ilan Goldfajn, "Financial Market Contagion in the Asian Crisis", *IMF Staff Papers* 46:2 (1999), 167-195.
- Baig, Taimur and Ilan Goldfajn, "Financial Market Contagion in the Asian Crisis", *IMF Staff Papers* 46:2 (1999), 167-195.
- Baur, Dirk and Niels Schulze, "Co-exceedances in Financial Markets: A Quantile Regression Analysis of Contagion", *Emerging Markets Review* 6:1 (2005), 21-43.
- Billio, Monica and Lorianna Pelizzon, "Contagion and Interdependence in Stock Markets: Have they been Misdiagnosed?", *Journal of Economics and Business* 55:5 (2003), 405-426.
- Bond, Shaun, Mardi Dungey and Renee Fry, "A Web of Shocks: Crises Across Asian Real Estate Markets", *Journal of Real Estate Finance and Economics* 32:3 (2006), 253-274.
- Brusco, Sandro and Fabio Castiglionesi, "Liquidity Coinsurance, Moral Hazard and Financial Contagion", *Journal of Finance* 62:5 (2007), 2275-2302.
- Caporale, Guglielmo, Andrea Cipollini and Nicola Spagnolo, "Testing for Contagion: a Conditional Correlation Analysis", *Empirical Finance* 12:3 (2005), 476-489.
- Cerra, Valerie and Sweta Chaman Saxena, "Contagion, Monsoons and Domestic Turmoil in Indonesia's Currency Crisis", *Review of International Economics* 10:1 (2002), 36-44.
- Corsetti, Giancarlo, Marcello Pericoli and Massimo Sbracia, " 'Some Contagion, Some Interdependence': More Pitfalls in Tests of Financial Contagion", *Journal of International Money and Finance* 24:8 (2005), 1177-1199.
- Dornbusch, Rudiger, Yung Chul Park and Stijn Claessens, "Contagion: Understanding How It Spreads", *The World Bank Research Observer* 15:2 (2000), 177-197.
- Dungey, Mardi and Vance Martin, "Unravelling Financial Market Linkages During Crises", *Journal of Applied Econometrics* 22:1 (2007), 89-119.
- Eichengreen, Barry, "Toward a New International Financial Architecture: A Practical Post-Asia Agenda", Washington: Institute for International Economics, (2002).
- Favero, Carlo and Francesco Giavazzi, "Is the International Propagation of Financial Shocks Non-linear? Evidence from the ERM", *Journal of International Economics* 57:1 (2002), 231-46.

- Forbes, Kristin and Roberto Rigobon, "No Contagion, Only Interdependence: Measuring Stock Market Co-movements", *Journal of Finance* 57:5 (2002), 2223-2261.
- Hartmann, Philipp, Stefan Straetmans and Casper de Vries, "Asset Market Linkages in Crisis Periods", *The Review of Economics and Statistics* 86:1 (2004), 313-326.
- Kaminsky, Graciela and Carmen Reinhart, "Financial Markets Under Stress", *Journal of Development Economics* 69:2 (2002), 451-470.
- Kiyotaki, Nobuhiro and John Moore, "Balance-Sheet Contagion", *The American Economic Review* 92:2 (2002), 46-50.
- Kleimeier, Stefanie, Thorsten Lehnert and Willem Verschoor, "Contagion Versus Interdependence: A Re-examination of Asian-Crisis Stock Market Comovements", LIFE Working Paper 2003-05 (2003).
- Kodres, Laura and Matthew Pritsker, "A Rational Expectations Model of Financial Contagion", *Journal of Finance* 57:2 (2002), 769-799.
- Lin, Wen-Ling, "Impulse Response Function for Conditional Volatility in GARCH Models", *Journal of Business and Economic Statistics* 15:1 (1997), 15-25.
- Mishkin, Frederic, "The Mexican Financial Crisis of 1994-99: An Asymmetric Information Analysis" (pp.149-182), in Scheherazade S. Rehman (Ed.), *Financial Crisis Management in Regional Blocs*, (Norwell: Kluwer, 1998).
- Pesaran, Hashem and Andreas Pick, "Econometric Issues in the Analysis of Contagion", *Journal of Economic Dynamics and Control* 31:4 (2007), 1245-1277.
- Pavlova, Anna and Roberto Rigobon, "The Role of Portfolio Constraints in the International Propagation of Shocks", *Review of Economic Studies*, forthcoming (2007).
- Rigobon, Roberto, "On the Measurement of the International Propagation of Shocks: is the Transmission Stable?", *Journal of International Economics* 61:2 (2003), 261-283.
- Rigobon, Roberto and Brian Sack, "Impact of Monetary Policy on Asset Prices", *Journal of Monetary Economics* 51:8 (2004), 1553-1575.
- Rothenberg, Thomas, "Identification in Parametric Models", *Econometrica* 39:3 (1971), 577-591.
- Yuan, Kathy, "Asymmetric Price Movements and Borrowing Constraints: A Rational Expectations Equilibrium Model of Crises, Contagion, and Confusion", *Journal of Finance* 60:1 (2005), 379-411.

Notes

¹Consistent with recent literature, we here refer to ‘pure’ contagion in the terminology of Dornusch, Park and Claessens (2000) and Kaminsky and Reinhart (2002), as distinct from crisis-driven changes in fundamental linkages.

²Theoretical models of contagion propose mechanisms such as information asymmetry and portfolio rebalancing (Kodres and Pritsker, 2002; Yuan, 2005), institutional and regulatory linkages, and relationship complexity (Allen and Gale, 2000; Brusco and Catiglionesi, 2007; Pavlova and Rigobon, 2007; Kiyotaki and Moore, 2002).

³Without de-meaning, the system could be expressed as $BY_t = \gamma\eta_t + u_t$ where η_t represents a common shock distributed $iidN(0, 1)$ with a vector of coefficients given by γ .

⁴In the case of non-zero mean data the following expressions would be complicated by the additional interactions of any common factors with the independent factors.

⁵One could ask, for example, ‘What is the effect on the volatility path of returns to the Thai stock market of a shock emerging from Hong Kong, during the Indonesian market crisis?’, and derive an impulse response function to estimate the size and duration of this specific effect.

⁶The role of contagion emanating from Hong Kong equity markets is highlighted in Corsetti, Pericoli and Sbracia (2005), Baur and Schulze (2005) and Bond, Dungey and Fry (2006) and statistically significant contagion from Korea to Thai equity markets is noted in Baig and Goldfajn (1999) and Cerra and Saxena (2002). Baig and Goldfajn (1999) also find links from Korea to Indonesia and Indonesia to Thailand.

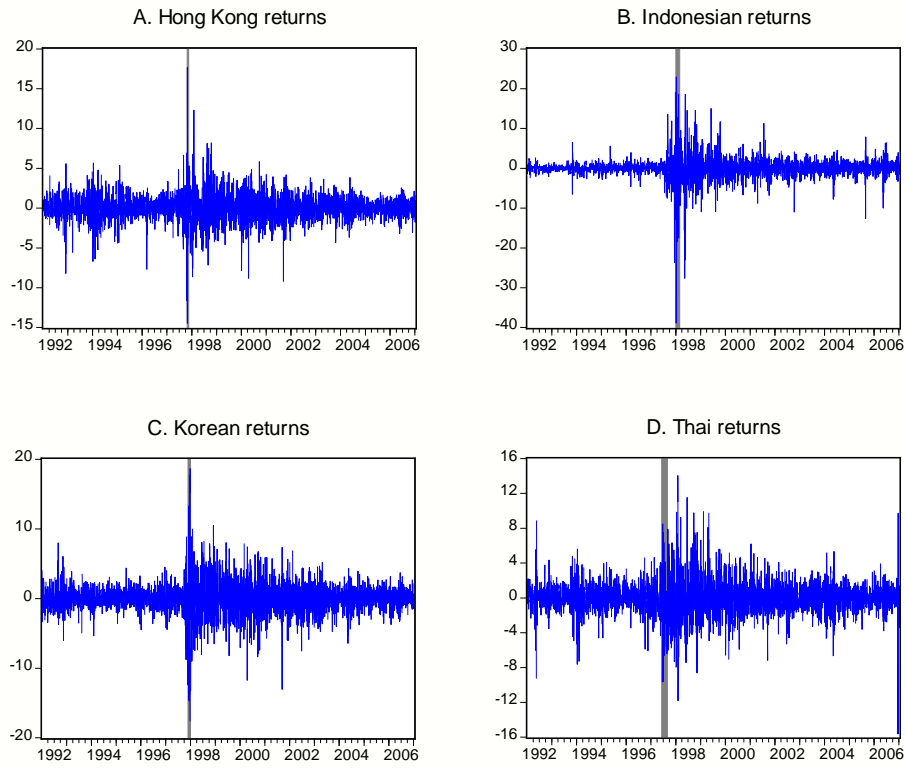
⁷Before estimation we removed all observations for which any market return was zero. This reduced the number of observations in the sample period from 3951 to 3608.

⁸The variance decomposition is constructed for all t possible conditionings in the sample. A histogram of these outcomes gives the mean and quantiles reported in Table 4.

⁹The results at 5 steps ahead confirm our classification.

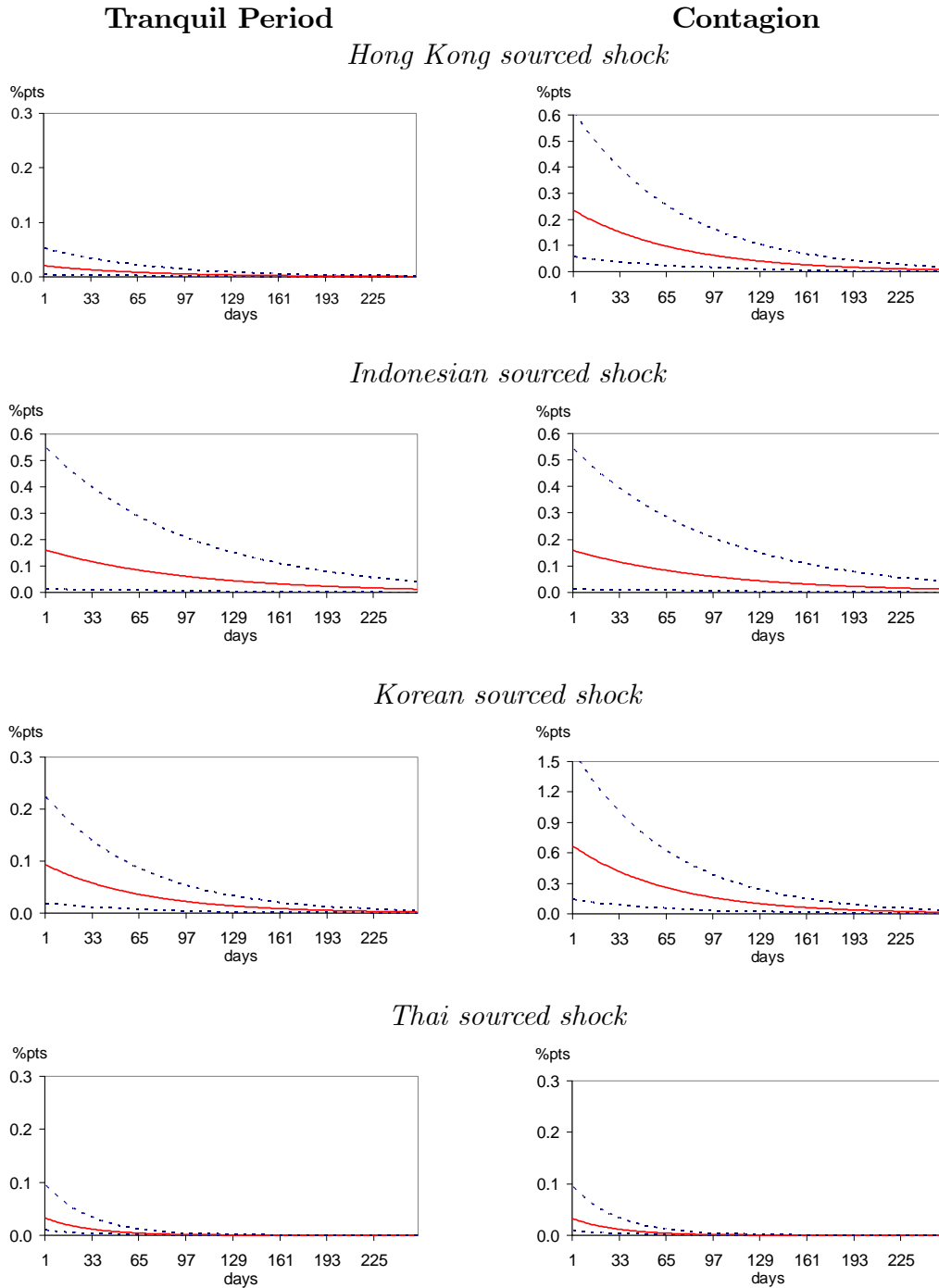
¹⁰All insignificant parameters are set to zero when variance decompositions and impulse response functions are computed.

Figure 1: Time Series of Daily Returns to Asian Equity Markets, January 1992 to January 2007.



Note: Each series is the residuals from a VAR(1). Grey bars indicate the period designated as crisis period in each country. Data sources are described in Table 1.

Figure 2: Impulse Response Functions of Equally Weighted Portfolio Variance to a Standard Deviation Shock for Periods of Tranquility and Contagion



Note: Vertical axes show the absolute increase in the daily variance of an equally-weighted portfolio of the equity indices n -days after a one standard deviation structural shock from each equity market. Impulse response functions are calculated conditioning on volatility at every time $= t$ in the sample. The dashed lines represent the 5th and 95th quantiles of the empirical distribution of the conditional impulse responses and the solid line represents the median.

Table 1:
Descriptive Statistics for Equity Returns: Tranquil Period and Crisis Periods

| | Hong Kong (HK) | Indonesia (IN) | Korea (KO) | Thailand (TH) |
|--|-------------------|-------------------|---------------|------------------|
| <i>Total Period: 1 January 1992-9 January 2007</i> | | | | |
| Mean | 0.000 | 0.000 | 0.000 | 0.000 |
| Max | 17.673 | 22.961 | 18.647 | 14.039 |
| Min | -14.467 | -38.888 | -17.572 | -15.622 |
| Std dev | 1.606 | 2.456 | 2.169 | 1.885 |
| J-B p-val | 0.000 | 0.000 | 0.000 | 0.000 |
| <i>Thai crisis: 10 June 1997 - 29 August 1997</i> | | | | |
| Mean | -0.061 | -0.642 | -0.053 | -0.500 |
| Max | 4.828 | 4.504 | 2.191 | 8.485 |
| Min | -5.071 | -7.515 | -2.592 | -9.629 |
| Std dev | 1.662 | 2.487 | 1.062 | 3.832 |
| J-B p-val | 0.001 | 0.007 | 0.884 | 0.930 |
| <i>Hong Kong crisis: 27 October 1997 - 17 November 1997</i> | | | | |
| Mean | -0.353 | -0.168 | -0.936 | -0.450 |
| Max | 17.673 | 11.881 | 8.832 | 6.335 |
| Min | -14.467 | -8.285 | -8.764 | -5.733 |
| Std dev | 6.767 | 5.155 | 4.936 | 3.776 |
| J-B p-val | 0.129 | 0.226 | 0.810 | 0.734 |
| <i>Korean crisis: 25 November 1997 - 31 December 1997</i> | | | | |
| Mean | 0.137 | -0.723 | -1.191 | -1.002 |
| Max | 4.698 | 19.060 | 18.647 | 5.486 |
| Min | -5.649 | -23.663 | -17.572 | -7.328 |
| Std dev | 2.435 | 7.671 | 10.916 | 2.942 |
| J-B p-val | 0.612 | 0.016 | 0.477 | 0.841 |
| <i>Indonesian crisis: 5 January 1998 to 27 February 1998</i> | | | | |
| Mean | -0.019 | -1.599 | 0.496 | 1.166 |
| Max | 12.295 | 22.961 | 9.957 | 14.069 |
| Min | -8.612 | -38.888 | -13.244 | -11.813 |
| Std dev | 3.982 | 11.600 | 5.193 | 5.310 |
| J-B p-val | 0.112 | 0.069 | 0.520 | 0.872 |

Note: Returns are computed as percentage log changes in the price indices for Hong Kong (Hang Seng HNGKNGI), Indonesia (Jakarta Composite JAKCOMP), Korea (Korea Composite KORCOMP) and Thailand (Bangkok SET BNGKSET) using daily series from Datastream, translated to US dollars before returns are computed. Sample runs from 2 January 1990 to 9 January 2007 but observations where there is a zero return from any series are removed before de-meaning, leaving 3608 days. Returns are de-meaned using a VAR(1) in the returns and the contemporaneous change in the daily 3-month US Treasury Bill secondary market mid-rate (FRTBS3M).

Table 2:
Parameter Estimation Results

| | | Hong Kong (HK) | Indonesia (IN) | Korea (KO) | Thailand (TH) |
|-------------------------------|--------------|-------------------|-------------------|-------------------|-------------------|
| <i>Tranquil</i> | | | | | |
| Hong Kong | $b_{i,HK}$ | | 0.103 (0.003) | -0.125 (0.156) | 0.268 (0.000) |
| Indonesia | $b_{i,IN}$ | 0.086 (0.001) | | 0.056 (0.006) | 0.154 (0.000) |
| Korea | $b_{i,KO}$ | 0.296 (0.000) | 0.002 (0.032) | | 0.094 (0.039) |
| Thailand | $b_{i,TH}$ | 0.027 (0.595) | 0.953 (0.457) | 0.031 (0.561) | |
| <i>Heightened Sensitivity</i> | | | | | |
| Hong Kong | $b_{s,i,HK}$ | | 0.554 (0.038) | 0.645 (0.007) | -0.500 (0.049) |
| Indonesia | $b_{s,i,IN}$ | 0.131 (0.266) | | 0.133 (0.538) | -0.127 (0.589) |
| Korea | $b_{s,i,KO}$ | -0.150 (0.299) | 0.741 (0.001) | | -0.002 (0.973) |
| Thailand | $b_{s,i,TH}$ | -0.174 (0.150) | -0.038 (0.692) | -0.098 (0.205) | |
| <i>Contagion</i> | | | | | |
| Hong Kong | $b_{c,i,HK}$ | | -2.050 (0.212) | -1.981 (0.253) | 0.440 (0.464) |
| Indonesia | $b_{c,i,IN}$ | 0.309 (0.512) | | -0.758 (0.033) | 0.230 (0.187) |
| Korea | $b_{c,i,KO}$ | -0.627 (0.160) | -0.636 (0.532) | | -0.689 (0.431) |
| Thailand | $b_{c,i,TH}$ | 0.431 (0.449) | 1.351 (0.373) | 0.903 (0.478) | |

Note: Parameter estimates for the model $BY_t = u_t$, where $B := (\mathbf{B}^* + \mathbf{B}_{c,s}\mathbf{D}_t)$ with $B_{c,s}D_t$ representing the linkages present in crisis periods. Contagion (indicated by subscript c) is modelled as the additional impact on asset markets in home country i during a crisis in foreign country j , given by the parameters $b_{c,ij}$ in each equation. Heightened sensitivity (indicated by subscript s) is given by the parameter $b_{s,ij}$ in each equation measuring the additional impact of foreign shocks during a domestic crisis. Each period of crisis is identified using an indicator variable $D_{i,t}$ which is one during the crisis in home country i and zero otherwise. The relevance of each instance of contagion and heightened sensitivity is tested by the significance of the parameters $b_{c,ij}$ and $b_{s,ij}$ where the columns represent the equations for each domestic market and the rows represent the impact of the foreign market. Estimation is by QML over daily de-meaned returns to equity market indices, sampling 2 January 1990 to 9 January 2007. P-values are in brackets.

Table 3:
GARCH parameter estimates

| | | Structural Shocks | | | |
|----------|-------------|-------------------|------------------|------------------|------------------|
| | i | Hong Kong | Indonesia | Korea | Thailand |
| Constant | ψ_i | 0.029 (0.035) | 0.073 (0.025) | 0.078 (0.003) | 0.113 (0.037) |
| ARCH | λ_i | 0.090 (0.000) | 0.187 (0.000) | 0.125 (0.000) | 0.169 (0.003) |
| GARCH | ζ_i | 0.897 (0.000) | 0.803 (0.000) | 0.860 (0.000) | 0.800 (0.000) |

Note: Parameter estimates for the conditional covariance matrix of the structural shocks, $G_t = \text{diag}[\psi + \lambda(\mathbf{u}_{t-1} \circ \mathbf{u}_{t-1})] + \zeta G_{t-1}$, where ψ is a 4×1 vector of constants, ψ_i , λ is a 4×4 diagonal matrix of ARCH coefficients and ζ is a 4×4 diagonal matrix of GARCH coefficients. Estimation is by QML over daily de-meaned returns to equity market indices, sampling 2 January 1990 to 9 January 2007. P-values are in brackets.

Table 4:
Mean Conditional Forecast Error Variance Decomposition (One Step Ahead)

| ε_i | Hong Kong | Indonesia | Korea | Thailand | portfolio |
|-------------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|
| <i>Tranquil</i> | | | | | |
| Hong Kong | 80.23 [61.80 - 95.23] | 1.11 [0.12-3.56] | 0.79 [0.20-2.38] | 5.26 [1.63-12.48] | 15.63 [4.87-39.38] |
| Indonesia | 3.18 [0.43-9.56] | 98.73 96.16-99.84] | 2.20 [0.44-6.16] | 5.50 [0.96-15.85] | 31.25 [10.53-63.95] |
| Korea | 16.59 [4.06-33.40] | 0.16 [0.03-0.41] | 97.01 [92.60-99.19] | 4.62 [1.19-11.12] | 39.20 [15.81-63.98] |
| Thailand | 0.00 [0.00-0.00] | 0.00 [0.00-0.00] | 0.00 [0.00-0.00] | 84.62 [68.78-94.93] | 13.92 [4.25-29.12] |
| <i>Heightened Sensitivity</i> | | | | | |
| Hong Kong | 81.48 [63.91-95.51] | 1.11 [0.12-3.56] | 1.75 [0.43-5.38] | 5.06 [1.53-12.10] | 19.09 [7.63-43.13] |
| Indonesia | 1.61 [0.21-4.85] | 98.73 [96.16-99.84] | 23.82 [7.21-53.55] | 0.85 [0.13-2.44] | 4.10 [0.87-4.10] |
| Korea | 16.91 [4.09-33.93] | 0.16 [0.03-0.41] | 74.43 [45.34-91.42] | 4.78 [1.16-11.65] | 56.16 [28.00-78.96] |
| Thailand | 0.00 [0.00-0.00] | 0.00 [0.00-0.00] | 0.00 [0.00-0.00] | 89.31 [78.50-96.55] | 20.66 [7.34-40.81] |
| <i>Contagion</i> | | | | | |
| Hong Kong | 70.29 [47.64-91.68] | 28.62 [9.78-61.58] | 19.35 [6.58-45.62] | 0.04 [0.01-0.09] | 31.53 [12.82-64.30] |
| Indonesia | 3.43 [0.51-10.18] | 28.09 [8.61-60.00] | 3.54 [0.73-10.01] | 5.01 [0.88-14.48] | 13.63 [3.33-35.11] |
| Korea | 26.27 [7.40-48.26] | 43.29 [18.56-67.49] | 77.11 [51.07-91.41] | 9.11 [2.42-21.15] | 52.06 [25.03-74.97] |
| Thailand | 0.00 [0.00-0.00] | 0.00 [0.00-0.00] | 0.00 [0.00-0.00] | 85.54 [68.76-96.05] | 2.79 [0.82-6.14] |

Note: Conditional one-step ahead error variance decompositions, computed for individual assets and an equally-weighted portfolio of market indices. Rows show the mean of empirical histogram of the conditional variance decompositions, conditioning on each standard deviation $g_{i,t}$ in the sample, and figures in square brackets are the 5th and 95th quantiles.