Unravelling Financial Market Linkages During Crises*

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October 2005

Abstract

An empirical model of multiple asset classes across countries is formulated in a latent factor framework. A special feature of the model is that financial market linkages during periods of financial crises, including spillover and contagion effects, are formally specified. The model also captures a range of common factors including global shocks, country and market shocks, and idiosyncratic shocks. The framework is applied to modelling linkages between currency and equity markets during the East Asian financial crisis of 1997-98. The results provide strong evidence that cross market links are important. Spillovers have a relatively larger effect on volatility than contagion, but both are statistically significant.

Keywords: Contagion, spillovers, indirect estimation, dynamics.

JEL Classification: C15, F31.

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*This research is supported by ARC Large Grant A00001350. We are grateful for helpful comments from the co-editor and referee, Renée Fry, Larry Harris, Adrian Pagan, Ghon Rhee, Roberto Rigobon and participants at the NYSE Conference on Global Equity Markets, the Q Finance Group Autumn meetings 2001, the IMF, MIT, the German Association of Investment Professionals and the Swiss Society of Investment Professionals.

1 Introduction

The problem presented by periods of financial crisis is that the fundamental relationships linking asset returns appear to break down, both across national boundaries and across asset classes. This presents serious problems for portfolio management as existing diversification strategies can be nullified by changes in the correlation between assets, leaving portfolios exposed to international shocks.

Typical examples of financial crises where the crisis has spread across national boundaries and across asset classes are the East Asian crisis of 1997-98, the Russian bond default of August 1998 and the Argentinian crisis of 2001-2. In each case, the crisis was sparked by a different style of shock. These shocks can be classified into three broad categories. First, a crisis may arise in a particular asset market within a particular country and then be transmitted to other markets and other countries. This is an example of an idiosyncratic shock, such as the Russian bond default where the repercussions were felt in both international bond, equity and currency markets. Second, the crisis may occur as a result of an asset market shock which impacts upon a specific asset class within a group of countries and is subsequently transmitted to other asset classes. The East Asian crisis provides an example of this situation, although there is debate as to whether equity or currency markets were the source of the shock. The third possibility is a country shock, where a shock in a country impacts upon all asset classes of that country, and then transmits to the asset markets of other countries. The effects of entering IMF negotiations, such as for Korea in late 1998 and for Argentina in 2001-2, provide examples of country shocks.

There is a large body of theoretical literature on the promulgation of crises that predicts that shocks transmit to both national and international asset markets across a range of financial assets. One class of models emphasises the role of common shocks. These shocks may represent information shocks (King and Wadhwani (1990), Calvo and Mendoza (2000)); liquidity shocks (Calvo (1999)); or shocks that result in portfolio rebalancing (Flemming, Kirby and Ostdiek (1998) and Kodres and Pritsker (2002)). Another class of models emphasises financial institutional linkages (Perry and Lederman (1998), Allen and Gale (2000)). A further class of models is based on the international asset pricing model of Solnik (1974), which emphasises the role of both national and international factors in pricing risk in asset markets (Bekaert and Hodrick (1992) and Dumas and Solnik (1995)). More recently, Pavlova and Rigobon (2003) develop a general framework to show how the presence of multiple asset classes can lead to contagious linkages between countries.

Despite the emphasis on modelling the dynamics of multiple markets during financial crises in the theoretical literature, the empirical financial crisis literature tends to concentrate on cross-border transmissions for a single asset class. For example, Eichengreen, Rose and Wyploz (1995, 1996), Cerra and Saxena (1999), Dungey and Martin (2004) look at currency markets; Bae, Karolyi and Stulz (2000), Forbes and Rigobon (2002) and Van Royen (2002) analyse equity markets; and Favero and Giavazzi (2002) and Dungey, Fry, Gonzaléz-Hermosillo and Martin (2005) examine bond markets. Another body of work concentrates on modelling the linkages between different asset classes during crises, but just within a particular country (Granger and Huang and Yang (2000), Fang and Miller (2002)). A number of papers examine different asset markets individually for the same period, for example Baig and Goldfajn (1999) look at currency markets, equity markets and sovereign bonds in the Asian crisis separately, but not the interactions between them. More recently, Hartmann, Straetmans and de Vries (2004) examine pairs of bond and equity markets across geographical borders and Ito and Hashimoto (2005) consider transmissions between currency and equity markets in the East Asian crisis.

The aim of this paper is to formulate and implement an empirical model of financial crises that incorporates a rich menu of assets across both asset classes and across national borders. The sheer dimensionality of the problem explains why there are few existing studies.[1] Although a vector autoregressive model of financial returns would provide a convenient starting point, adapting this to account for the volatility clustering common in high frequency data results in a large number of parameters. Longin and Solnik (1995) and Malliaroupulos (1997) attempt to circumvent this by estimating sub-models corresponding to individual countries, but this restriction may rule out potentially important links. The solution adopted in this paper to the parameter dimensionality problem of empirical models of financial crises is to recognise that there

[1]Some empirical models that focus on a range of asset markets do exist. Kaminsky and Reinhart (2001) use principal components to identify commonalities in equities, currencies and bonds across a range of countries; see also Kaminsky, Lizondo and Reinhart (1998), Berg and Pattillo (1999). However, both of these latter models assume constant volatility structures thereby ignoring the changing volatility structures that characterise asset returns during financial crises.

is commonality in the empirical characteristics of financial returns, especially in the case of time-varying volatility. This suggests that a small set of latent factors can be used to represent common international and national factors which provide a parsimonious representation of the key empirical features of asset returns (Diebold and Nerlove (1989), Engle, Ito and Lin (1990), and Dungey, Martin and Pagan (2000)). This set includes global, market and country factors to capture market fundamentals; dynamic adjustments to represent cross-market spillovers; and additional movements over and above market fundamentals during crisis periods which are typically called contagion. The definition of spillover and contagion effects draws on the existing theoretical literature such as Masson (1999) and essentially views contagion as the effect of residual shocks once the usual linkages have been accommodated. Overviews of the literature on contagion may be found in Dornbusch, Park and Claessens (2000) and Pericoli and Sbracia (2003).

Estimation of latent factor GARCH models by standard maximum likelihood methods is numerically infeasible, and hence a simulation estimator is adopted based on the work of Gourieroux, Monfort and Renault (1993), Duffie and Singleton (1993) and Gallant and Tauchen (1996). The estimation strategy consists of simulating the latent factors to generate a set of simulated asset returns. This estimator is consistent and under certain regularity conditions is asymptotically equivalent to the maximum likelihood estimator.

An important feature of the proposed latent factor approach to modelling financial crises is that it circumvents the need for using proxy variables to identify the common factors (Eichengreen, Rose and Wyploz (1995, 1996) and Sachs, Tornell and Velasco (1996)). This is especially useful for high frequency data investigations where the range of proxy variables that can be used is limited by data availability. In addition the proposed model provides a convenient form for decomposing the volatility of returns in asset markets across countries into the relative contributions of alternative factors, providing a framework to assess the relative strengths of different linkages during financial crises. Previous work by Dungey, Fry, Gonzaléz-Hermosillo and Martin (2005a) shows that the proposed modelling strategy encompasses existing many of the existing empirical approaches to modelling contagion, including Eichengreen, Rose and Wyplosz (1995, 1996), Forbes and Rigobon (2002), Favero and Giavazzi (2002) and Bae, Karolyi and Stulz (2003).

To illustrate this methodology the proposed model is applied to studying the linkages between equity and currency markets during the East Asian financial crisis of 1997 to 1998.[2] As well as addressing interesting empirical issues, this application demonstrates the ability of the modelling approach to deal with situations where there is no clear pre-crisis period data available, due in this case to the change from fixed to floating exchange rates associated with the crisis. The main empirical result is that there is strong evidence of the importance of cross-market linkages, with spillovers and contagion across markets both being found to be statistically significant. A comparison of the results with pre-crisis equity market returns suggests the important contribution of contagion and spillovers in the observed increased in volatility between pre-crisis and crisis periods. The results provide empirical support for analyzing currency and equity markets jointly and suggest that analyses of financial crises focussing on a single asset market are potentially misspecified.

The rest of the paper is organized as follows. The latent factor model of financial crises is developed in Section 2 beginning with a model that allows for various types of common shocks, which is then expanded to include additional transmission mechanisms arising from spillovers and contagion. The model is applied in Section 3 to the East Asian financial crisis of 1997-98, with concluding comments contained in Section 4.

2 A Model of Crisis Transmission

This section develops a dynamic latent factor model of the transmission of financial crises within asset markets of countries as well as across national borders. The structure of the model is related to the ICAPM models originating with Solnik (1974) whereby asset returns are assumed to be driven linearly by a set of factors which are either common to assets markets (systematic) or are idiosyncratic (nonsystematic) to a particular market. These models have been used to analyse equity markets (King, Sentana and Wadhwani (1994), Lin, Engle and Ito (1994), Karolyi (1995), and Bekaert, Harvey and Ng (2003)), fixed interest markets (Dungey, Martin and Pagan (2000)) and currency markets (Diebold and Nerlove (1989), Mahieu and Schotman (1994)). More recently

[2] The potential for links to fixed interest markets are not incorporated here, as there was little impact of the Asian crisis on bond markets, particularly compared with other crises; see Dungey, Fry, Gonzaléz-Hermosillo and Martin (2005c).

Flood and Rose (2003) have used a similar approach to model the covariance structure of asset returns to test for market integration.

Various types of common factors are specified in the model, including global factors that impact upon all financial markets across all countries, market factors which only impact upon a particular class of financial assets in countries, and country factors which capture the common effects of shocks to asset markets within a country. In modelling linkages during financial crises, two additional channels are considered, motivated by existing models of contagion. The first consists of spillovers which are modelled as the lagged effects of market factors in one class of asset markets on another class.[3] The second channel arises from contagion which is modelled as the effects of additional shocks of the market factor in one class of assets on another class over and above the effects of common factors that operate during non-crisis periods. This decomposition of factors is motivated by the classification discussed in Masson (1998, 1999). In presenting the model, asset market linkages arising from common shocks are first discussed. The model is then extended to allow for linkages due to spillovers and contagion.

2.1 Common Shock Linkages

Building on standard latent factor finance models, the proposed model consists of $N+1$ countries each with J asset markets, a total of $(N+1)\,J$ asset markets. Let $R_{i,j,t}$, represent the returns of country $i = 0, 1, ..., N$, on asset class $j = 1, 2, ...J$, at time t. Further assume that the returns have zero mean by simply subtracting the sample means from the actual returns. In the following $i = 0$, represents the numeraire country. Consider the following linear factor representation of asset returns

$$R_{i,j,t} = \delta_{i,j} W_t + \lambda_{i,j} M_{j,t} + \omega_{i,j} C_{i,t} + \phi_{i,j} u_{i,j,t}. \tag{1}$$

The first three factors, W_t, $M_{j,t}$ and $C_{i,t}$, capture a broad range of shocks that are either common to all asset markets or particular sub-groupings. The factor W_t, captures the simultaneous effects of common global (world) news on all asset markets in all countries with the impact measured by the parameter, $\delta_{i,j}$. The factor $M_{j,t}$, represents the asset

[3] The term spillovers is adopted from Masson (1999). An alternative term is fundamentals-based contagion due to Kaminsky and Reinhart (2000) and Dornbusch, Park and Claessens (2000).

market factor as it captures shocks that jointly impact upon all assets of a particular class j, across all countries at time t. The strength of the asset market factor on returns is determined by the loading parameter $\lambda_{i,j}$. The third and final common factor is given by $C_{i,t}$. This is referred to as the country factor as it captures those shocks that are specific to the asset markets of a particular country. The impact of these shocks on national asset markets is governed by the parameter $\omega_{i,j}$. A property of these shocks is that they are systematic and cannot be diversified away. This is in contrast to the final factor in (1), $u_{i,j,t}$, which represents idiosyncratic shocks of a particular asset market within a particular country. These shocks are diversifiable by adopting an international portfolio.

For the case where $R_{i,j,t}$ represents currency returns, the shocks of the numeraire country $C_{0,t}$, are also included in the factor representation in (1). In contrast to the impact of the other factors on asset returns, the effect of a shock in this case is constrained to be the same across all country exchange rates arising from the imposition of a no-arbitrage condition on the factor structure. This restriction on the factor loadings of the numeraire country is motivated by the work of Mahieu and Schotman (1994), and Dungey, Martin and Pagan (2000), where the effects of a shock in the numeraire country on bilateral exchange rates must have the same impact on all exchange rates as it is the same shock. A feature of this restriction is that it is not necessary to estimate the loadings for cross-rates as they can be extracted from a panel of exchange rates against a common numeraire currency (Dungey, Martin, Pagan (2000)). The formal exposition of this is given in Appendix A.

To complete the specification of the factor model, it is necessary to specify the dynamics of the latent factors. As all asset returns in the model are totally driven by a set of latent factors, any features observed in the data need to be modelled via these factors. One important feature is the volatility clustering commonly observed in asset returns. This empirical feature of the data is especially true for asset returns during periods of financial crises. Another feature of asset returns that tends not to be as significant as the volatility clustering feature, is serial correlation in the mean (Pesaran and Timmermann (1995)).[4]

[4]Mody and Taylor (2003) also adopt a factor model to analyse financial crises. However, they ignore the important time-varying volatility characteristics by specifying factors that have autoregressive representations with constant variances. This structure does have the advantage that it can be estimated using a Kalman filter, but at the cost of misspecifying the volatility structure.

The dynamics of the factors are specified as follows. The dynamics in the factor means are specified as first order autoregressive processes.

$$\begin{aligned} W_t &= \rho_w W_{t-1} + \nu_t \\ M_{j,t} &= \rho_{m,j} M_{j,t-1} + \varepsilon_{j,t} \\ C_{i,t} &= \rho_{c,i} C_{i,t-1} + \zeta_{i,t} \\ u_{i,j,t} &= \rho_{u,i,j} u_{i,j,t-1} + \eta_{i,j,t}. \end{aligned} \tag{2}$$

A higher order autoregressive processes could easily be incorporated, however a first order autocorrelation structure is sufficient for most financial returns, which proves to be the case for the empirical example of this paper, as explicitly shown in Section 3.1. The disturbances ν_t, $\varepsilon_{j,t}$, $\zeta_{i,t}$ and $\eta_{i,j,t}$ are assumed to be distributed as

$$\begin{aligned} \nu_t &\sim N(0, h_{w,t}) \\ \varepsilon_{j,t} &\sim N(0, h_{m,j,t}) \\ \zeta_{i,t} &\sim N(0, h_{c,i,t}) \\ \eta_{i,j,t} &\sim N(0, h_{u,i,j,t}), \end{aligned} \tag{3}$$

where the conditional volatilities are specified as $GARCH(1,1)$. The conditional volatilities in equation (3) are given by,

$$\begin{aligned} h_{w,t} &= 1 - \alpha_w - \beta_w + \alpha_w \nu_{t-1}^2 + \beta_w h_{w,t-1} \\ h_{m,j,t} &= 1 - \alpha_{m,j} - \beta_{m,j} + \alpha_{m,j} \varepsilon_{j,t-1}^2 + \beta_{m,j} h_{m,j,t-1} \\ h_{c,i,t} &= 1 - \alpha_{c,i} - \beta_{c,i} + \alpha_{c,i} \zeta_{j,t-1}^2 + \beta_{c,i} h_{c,i,t-1} \\ h_{u,i,j,t} &= 1 - \alpha_{u,i,j} - \beta_{u,i,j} + \alpha_{u,i,j} \eta_{i,j,t-1}^2 + \beta_{u,i,j} h_{u,i,j,t-1}. \end{aligned} \tag{4}$$

The restriction that the $GARCH(1,1)$ equations have intercepts equal to one minus the sum of the their GARCH parameters serves as a normalisation to identify the volatility of each factor. From the properties of GARCH models, this normalisation restricts the unconditional variances to be equal to unity (Diebold and Nerlove (1989)). As with the conditional mean specifications of the factors, higher order GARCH models can be entertained. However, a $GARCH\,(1,1)$ serves as a useful specification for capturing many of the conditional volatility features of asset returns (Bollerslev, Chou and Kroner (1992)) and provides an appropriate benchmark for the properties of this type of series (Engle (2004)). The characteristics of the data used in the application of this paper confirm this general empirical regularity in the data and accept a GARCH(1,1) characterisation in preference to higher orders.

One way to interpret the model is that it provides an alternative, albeit more informative, way to interpret the variance covariance matrix of asset returns. To highlight this feature of the model, the unconditional volatility of asset returns is decomposed into the contributions of the various factors as

$$E\left[R_{i,j,t}^2\right] = \frac{\delta_{i,j}^2}{1-\rho_w^2} + \frac{\lambda_{i,j}^2}{1-\rho_{m,j}^2} + \frac{\omega_{i,j}^2}{1-\rho_{c,i}^2} + \frac{\phi_{i,j}^2}{1-\rho_{u,i,j}^2}, \tag{5}$$

which immediately follows from the assumption that the factors are independent. This expression provides a convenient representation to quantify the relative contributions of the four factors to the overall volatility of each asset return, with the contribution of the systematic factors given by the first three terms and the contribution of the idiosyncratic factor given by the last term in (5).

The interaction between asset markets can be analysed by decomposing the covariances of the asset returns into the contributions of the pertinent factors. It is informative to highlight three sub-classes of models which are special cases of the more general factor model specified in (1).

1. *Commonality across national borders of the same asset class*

   The covariance between country i and country k for the j^{th} asset is given by

   $$E\left[R_{i,j,t}R_{k,j,t}\right] = \frac{\delta_{i,j}\delta_{k,j}}{1-\rho_w^2} + \frac{\lambda_{i,j}\lambda_{k,j}}{1-\rho_{m,j}^2}. \tag{6}$$

   Comovements between asset returns is determined jointly by the impact of the world factor on all asset markets (the first term) and the j^{th} asset market factor (the second term) which impacts upon all asset markets in that asset class. This sub-class of models has been studied by Eichengreen, Rose and Wyploz (1995, 1996), Bae, Karolyi and Stulz (2000), Forbes and Rigobon (2002), Favero and Giavazzi (2002), amongst others.

2. *Commonality across asset classes within a country*

The covariance between asset markets j and l in country i, is given by

$$E\left[R_{i,j,t}R_{i,l,t}\right] = \frac{\delta_{i,j}\delta_{i,l}}{1-\rho_w^2} + \frac{\omega_{i,j}\omega_{i,l}}{1-\rho_{c,i}^2}. \tag{7}$$

In this case, comovements between asset returns is determined jointly by the impact of the world factor on all asset markets (the first term) and the shocks which are specific to the i^{th} country (the second term). This sub-class of models has been investigated by Granger, Huang and Yang (2000) and Fang and Miller (2002).

3. *Commonality across national borders and across asset classes*

The covariance between asset market j in country i and asset market l in country k, is given by

$$E\left[R_{i,j,t}R_{k,l,t}\right] = \frac{\delta_{i,j}\delta_{k,l}}{1-\rho_w^2}. \tag{8}$$

In this case any common movements in asset returns is solely determined by the world factor and how it impacts upon asset markets in all countries. If asset returns respond the same way to the world factor, then the signs of the loadings of the world factor are the same thereby yielding a positive covariance. For the opposite case where the signs on the loadings of the world factor are reversed, the covariance of asset returns is negative. This model is equivalent to a one-factor international capital asset pricing model discussed by Solnik (1974), whereby the risk of an asset is determined by its beta, which is given by the parameter $\delta_{i,j}$ in (5).[5]

The expressions of the variances and covariances in equations (5) to (8) are unconditional quantities. There are also conditional analogues to these unconditional quantities. For example, the conditional volatility based on information at time $t-1$, between asset returns in countries i and k for the j^{th} asset class is

$$\begin{aligned} E_{t-1}\left[R_{i,j,t}R_{k,j,t}\right] &= \left(\frac{\delta_{i,j}\delta_{k,j}}{1-\rho_w^2}\right)\left(1-\alpha_w-\beta_w+\alpha_w\nu_{t-1}^2+\beta_w h_{w,t-1}\right) \\ &\quad + \left(\frac{\lambda_{i,j}\lambda_{k,j}}{1-\rho_{m,j}^2}\right)\left(1-\alpha_{mj}-\beta_{mj}+\alpha_{mj}\varepsilon_{j,t-1}^2+\beta_{mj}h_{mj,t-1}\right). \end{aligned} \tag{9}$$

[5]One difference between the ICAPM model and the factor model specified here, is that in the former model a proxy variable is chosen to represent world returns, whereas in the present framework it is identified internally within the model using the characteritics of all asset returns studied.

This expression highlights the parsimony features of the factor specification for modelling the multivariate volatility structure of asset returns. In general, there is a maximum of $((N+2)J+N+2)$ $GARCH$ factor specifications to model a total of $(N+J+1)$ conditional asset return variances and $((N+J+1)(N+J)/2)$ conditional asset return covariances. For example, if there are 7 countries including the numeraire country $(N=6)$ and two asset markets $(J=2)$, this is a nine-variate system where the total number of conditional variances and covariances that need to be modelled is 45.[6] This contrasts with a maximum of 24 conditional volatility structures in the case of the factor model. Given the empirical commonality features in asset return volatilities, further reductions in the number of factors and their corresponding GARCH specifications, are possible.

2.2 Spillover and Contagious Linkages

The common factor specification in (1) models comovements in asset returns through various types of common shocks. This framework is now extended in a number of directions to allow for additional linkages between asset markets during a crisis. In specifying these additional linkages in the model attention is focussed on the source of the crisis. Three specifications are investigated depending on whether the source of the shock is specific to a particular asset market within a particular country (Idiosyncratic), arises from a specific asset market (Market), or arises in a particular country (Country). In developing these specifications of the source of the crisis, further refinements are required to distinguish between linkages due to spillovers and those due to contagion, following the classification suggested by Masson (1998, 1999); see also Dungey and Martin (2004).

The taxonomy used in this model views the difference between contagion and spillovers as referring to the timing of the initial impact of the shock. Spillovers are the transmission at time t or later of shocks which occurred at time $t-1$, hence there is a sense in which they are a response to expected propogation paths. Contagion, however, is the contemporaneous or later transmission of unexpected shocks; in Masson's terminology this is the residual transmissions after accounting for all other sources of transmissions including spillovers.

[6] This is the dimension of the model estimated in the empirical section.

2.2.1 Idiosyncratic Source

Consider the case where the source of the shock to the financial system of $N+1$ countries and J asset classes is located in a particular country's asset market, $u_{i,j,t}$. Denote the source country and asset as $i = k$ and $j = s$, so that the shock is contained within the factor $u_{k,s,t}$. Equation (1) is now augmented as

$$\begin{aligned} R_{i,j,t} &= \delta_{i,j} W_t + \lambda_{i,j} M_{j,t} + \omega_{i,j} C_{i,t} + \phi_{i,j} u_{i,j,t} \qquad i \neq k, j \neq s, \\ &\quad + \sum_{l=1}^{L} \theta_{i,j,l} u_{k,s,t-l} + \sum_{l=0}^{L} \gamma_{i,j,l} \eta_{k,s,t-l}, \end{aligned} \tag{10}$$

where $\eta_{k,s,t}$ is defined in (2) as the unanticipated shock of $u_{k,s,t}$ based on $t-1$ information.

The second last term in (10) allows for the effects of a crisis in the j^{th} asset market of country i, to impact upon all other asset markets. This shock is initially felt with a lag of one period as asset markets adjust to the crisis, which is assumed to continue for L periods. The strength of these linkages are governed by the parameter $\theta_{i,j,l}$. This shock is referred to as a spillover as it reflects information that is available to agents in other markets at time $t-1$.

The last term in (10) allows for the unanticipated component of the shock $\eta_{k,s,t}$, to have an impact on asset markets at t. This shock is unanticipated as it is not contained in the information set of agents which is based on information up to time t. This channel is referred to as contagion as it occurs over and above the linkages which are included in the information sets of agents. Equation (10) also allows for the contagion channel to occur over time with the strength of dynamics determined by $\gamma_{i,j,l}$.

2.2.2 Asset Market Source

Now consider the situation where there is general turmoil in one particular asset class which is transmitted to other asset classes. Denote the source asset class as $j = s$, so that the shock is contained within the factor $M_{s,t}$. These linkages are captured by augmenting (1) as

$$
\begin{aligned}
R_{i,j,t} &= \delta_{i,j} W_t + \lambda_{i,j} M_{j,t} + \omega_{i,j} C_{i,t} + \phi_{i,j} u_{i,j,t} \qquad j \neq s, \\
&+ \sum_{l=0}^{L} \theta_{i,j,l} M_{s,t-l} + \sum_{l=0}^{L} \gamma_{i,j,l} \varepsilon_{s,t-l},
\end{aligned} \tag{11}
$$

where $\varepsilon_{s,t}$ is defined in (2) as the unanticipated shock of the market factor $M_{s,t}$, based on $t-1$ information. As before, both spillovers (the second last term) and contagion (the last term) are allowed for, with the strengths of these linkages controlled by $\theta_{i,s,l}$ and $\gamma_{i,s,l}$, respectively. This specification provides a parsimonious representation of modelling a large number of potential linkages between asset markets through the asset market factor $M_{s,t}$ and its associated unanticipated term $\varepsilon_{s,t}$. This specification can be further extended by including feedback between asset market classes. This additional specification is entertained in the empirical application in Section 3, where the focus is on modelling the cross-market linkages between equity and currency markets during the East Asian financial crisis.

2.2.3 Country Source

The last scenario considered is where there is a country-specific event that impacts on all asset markets within that country, which, in turn, are transmitted to other asset markets in other countries. Denote the source country as $i = k$, so that the shock is contained within the factor $C_{k,t}$. Equation (1) is now extended as

$$
\begin{aligned}
R_{i,j,t} &= \delta_{i,j} W_t + \lambda_{i,j} M_{j,t} + \omega_{i,j} C_{i,t} + \phi_{i,j} u_{i,j,t} \\
&+ \sum_{l=0}^{L} \theta_{i,j,l} C_{k,t-l} + \sum_{l=0}^{L} \gamma_{i,j,l} \zeta_{k,t-l}, \qquad i \neq k,
\end{aligned} \tag{12}
$$

where $\zeta_{k,t}$ is defined in (2) as the unanticipated shock of the country factor $C_{k,t}$, based on $t-1$ information. As before, both spillovers (the second last term) and contagion (the last term) are allowed for, with the strengths of these linkages controlled by $\theta_{i,s,l}$ and $\gamma_{i,s,l}$, respectively. As with the asset market shock specification in (11), this specification can be extended further by including feedback between countries.

3 Currency and Equity Markets During the East Asian Crisis

The multi-factor model of financial crises is now applied to testing the transmission mechanisms between currency and equity markets during the East Asian financial crisis of 1997-98. Six countries are used in the empirical analysis. From the East Asian region the countries are Indonesia, Korea, Malaysia and Thailand, which are chosen to identify the linkages amongst financial markets within the same geographical region which are directly exposed to the crisis. The two other countries included in the analysis are the US and Australia. Both of these countries are included as they provide a test of transmission mechanisms to countries outside of the East Asian region which have well developed financial markets, but differ in size. The US is used to identify common shocks because of its size, as well as in identifying numeraire shocks as all exchange rates are denominated in terms of the US dollar.

The focus on currency and equity markets is motivated by the observation that the East Asian financial crisis of 1997-98 is usually referred to as a currency crisis with the depreciation of the Thai baht on 2nd July 1997, representing the start of the crisis; see for example Baig and Goldfajn (1999) and Karolyi (2003). However, McKibbin and Martin (1998) and Ito and Hashimoto (2005) have argued that the seeds of the crisis were sown in equity markets and transmitted from there to currencies, while Goldstein (1998) attributes the source of contagion during the crisis to Thailand generally.

3.1 Data

The sample period begins on 2 July 1997, and ends on 31 August 1998, a total of 304 daily observations. This period includes the float of the Thai baht on 2 July 1997, the float of the Indonesian rupiah on 14 August 1997 and the float of the Korean won on 22 December 1997. The period also encompasses the turmoil in stock markets beginning mid October 1997 and ending mid November 1997, but ceases prior to the fixing of the Malaysian ringgitt in September 1998. Data sources are given in Appendix B.

All financial returns are expressed in percentages and computed as differences of the natural logarithms of their prices. Each return is demeaned by subtracting the sample mean from each series. In the case of Korea, an AR(1) filter is used to extract the significant autocorrelation structure observed in the currency returns data.[7] This means that the effective sample period consists of $T = 303$ observations beginning on 3 July 1997. The properties of this data are by now well-known with most of the largest movements in currency and equity returns of the four Asian financial markets occurring near the end of 1997 to early 1998. In order to develop the appropriate form of the specification of the model described in Section 2 some preliminary analysis of the data set is first undertaken.

3.1.1 Contemporaneous Structure

Table 1 gives three sets of contemporaneous correlations of returns: correlation amongst the six equity markets, correlation amongst the five currency markets and cross-market correlations between currencies and equities for all countries. The asymptotic standard error is $T^{-0.5} = 303^{-0.5} = 0.057$.

There are strong correlations amongst the East Asian equity markets as well as with the Australian equity market. The correlations with the US equity market are smaller, but are still statistically significant at the 5% level in three cases (Korea, Thailand and Australia).

There are strong correlations amongst the currency markets, especially in the case of Indonesia, Thailand and Malaysia. The Australian currency market also exhibits strong correlations with these three currency markets. The Korean currency market tends to be more idiosyncratic, although the correlation with the Thai currency market is nonetheless statistically significant.

The last matrix in Table 1 gives the cross-market correlations. The first five diagonal entries give the correlations between equity and currency markets within a country, whereas the remaining entries give the correlations across both markets and countries. All correlations are negative. There are statistically significant cross-market correlations within countries, with Malaysia (-0.447) exhibiting the largest followed by Thailand (-0.289). There are also a number of statistically significant correlations across markets within different countries. The strongest correlations are between the Malaysian currency market and the equity markets in Indonesia (-0.236), Thailand (-0.432) and Australia (-0.247).

[7] The Korean won was fixed until 22 December 1997.

Table 1:
Correlation matrices of equity and currency returns.

Equity markets

	Korea	Indon	Thai	Malay	Aust	US
Korea	1.000					
Indon	0.137	1.000				
Thai	0.281	0.432	1.000			
Malay	0.261	0.374	0.412	1.000		
Aust	0.237	0.321	0.336	0.334	1.000	
US	0.144	0.042	0.123	0.097	0.144	1.000

Currency markets

	Korea	Indon	Thai	Malay	Aust
Korea	1.000				
Indon	0.111	1.000			
Thai	0.183	0.371	1.000		
Malay	0.087	0.423	0.569	1.000	
Aust	0.080	0.228	0.341	0.427	1.000

Equity/Currency markets

	Korea	Indon	Thai	Malay	Aust
Korea	-0.171	-0.099	-0.075	-0.200	-0.141
Indon	-0.166	-0.101	-0.257	-0.217	-0.178
Thai	-0.121	-0.089	-0.289	-0.248	-0.167
Malay	-0.096	-0.236	-0.432	-0.447	-0.247
Aust	-0.114	-0.066	-0.055	-0.101	-0.134
US	-0.082	-0.055	-0.077	-0.109	-0.135

Table 2:
VAR lag structure tests consisting of the eleven returns series and a constant: Akaike information criterion (AIC) and Hannan-Quinn information criterion (HIC).

Lag	AIC	HIC
0	45.220	45.274
1	44.579	45.235
2	44.863	46.120
3	44.881	46.739
4	45.086	47.544
5	45.151	48.210

3.1.2 Autocorrelation Structure

To provide a preliminary identification of the autocorrelation structure of the returns series and hence the lag lengths needed in specifying the factor model, VARs containing all eleven returns series with lag lengths ranging from zero lags to five lags are estimated. The results are summarised in Table 2 which gives the Akaike information criterion (AIC) and Hannan-Quinn information criterion (HIC) for each lag length. The AIC and HIC statistics are both minimised for a lag length of one.

3.1.3 Conditional Volatility Structure

A preliminary analysis of the volatility structure of the eleven returns series is now conducted by estimating GARCH(1,1) models for each of the series. The model is

$$\begin{aligned} r_t &= \mu_t + u_t \\ u_t &= \sqrt{h_t} z_t \\ h_t &= \alpha_0 + \alpha_1 u_{t-1}^2 + \beta_1 h_{t-1} \\ u_t &\sim N(0, h_t), \end{aligned}$$

where r_t is a particular returns series and μ_t is a time-varying mean which contains an intercept and the first lag of all eleven returns series. This analysis not only provides an initial identification of both the number of common factors underlying conditional volatility movements, but it also provides insight into the dynamics of these common factors.

The results are given in Table 3. The point estimates of α_1 and β_1 show some commonality amongst the volatility structure of the returns series. The results suggest that the estimated model can be categorised into three groups depending upon the size of the estimate of β_1, which controls the persistence of shocks to conditional volatility: High persistence (equity markets in Korea and Indonesia, currency markets in Thailand, Malaysia and Australia); medium persistence (equity markets in Thailand and the US, currency markets in Korea and Indonesia); low persistence (equity markets in Malaysia and Australia).

Some diagnostics of the GARCH(1,1) estimated models are also presented in Table 3. A test of first order ARCH in the standardised residuals reveals no evidence of higher order lag structures in the conditional variance. The Schwarz information criterion statistic is reported for the GARCH(1,1) as well as for the GARCH(1,2) and GARCH(2,1) models. For nearly half of the estimated models for the eleven returns series, the Schwarz statistic is minimised for the most parsimonious model, namely the GARCH(1,1) model.

3.2 Model Specification

In this section, an empirical model used to test for contagion is specified based on the general theoretical framework of Section 2 drawing on the empirical characteristics of the dataset discussed above. Given that the East Asian crisis is characterised as a cross asset market crisis in the Introduction the appropriate specification is based on equation (11). The number of asset markets is $N = 2$, consisting of equity $(j = q)$ and currency $(j = x)$. The number of countries is $N + 1 = 6$, with the US representing the numeraire currency $(i = 0)$. In specifying the empirical model, the key empirical issues are the treatment of time zones, the structure of the dynamics and the form of the contagious linkages.

The empirical analogue of equation (11) for equity returns $(j = q)$ is specified to have the following linear factor structure

$$\begin{aligned} R_{i,q,t} &= \delta_{i,q} W_t + \lambda_{i,q} M_{q,t} + \omega_{i,q} C_{i,t} + \phi_{i,q} u_{i,q,t} + \theta_{i,x,1} M_{x,t-1} \\ &\quad + \gamma_{i,x,0} \varepsilon_{x,t} + \tau_i u_{0,q,t-1}, \qquad i = 0, 1, \cdots, 5. \end{aligned} \tag{13}$$

The first four factors are the world (W_t), equity market $(M_{q,t})$, country $(C_{i,t})$ and

Table 3:

Conditional volatility estimates of GARCH(1,1) models of equity and currency returns with standard errors given in parentheses. The diagnostics reported are: ARCH(1) is the p-value from testing for first order ARCH in the standardised residuals; SIC(p,q) is the Schwarz information criterion of a GARCH(p,q) model. The mean equation of each returns series contains a constant and the first lag of all 11 returns series.

	$\widehat{\alpha}_1$	$\widehat{\beta}_1$	ARCH(1)	SIC(1,1)	SIC(1,2)	SIC(2,1)
Equity Markets						
Korea	0.079	0.923	0.423	5.107	5.104	5.125
	(0.029)	(0.025)				
Indonesia	0.190	0.824	0.925	4.876	4.987	4.893
	(0.041)	(0.028)				
Thailand	0.231	0.628	0.602	4.671	4.690	4.660
	(0.086)	(0.105)				
Malaysia	0.365	0.349	0.499	5.005	4.982	5.011
	(0.121)	(0.138)				
Australia	0.221	0.406	0.855	2.611	2.616	2.624
	(0.087)	(0.246)				
US	0.239	0.606	0.375	3.294	3.248	3.281
	(0.070)	(0.153)				
Currency Markets						
Korea	0.384	0.731	0.985	3.048	3.058	3.065
	(0.078)	(0.040)				
Indonesia	0.457	0.711	0.382	5.915	5.931	5.891
	(0.073)	(0.029)				
Thailand	0.058	0.926	0.325	3.983	3.995	3.981
	(0.026)	(0.033)				
Malaysia	0.094	0.895	0.970	3.860	3.878	3.878
	(0.023)	(0.021)				
Australia	0.075	0.887	0.404	2.481	2.486	2.489
	(0.034)	(0.060)				

idiosyncratic ($u_{i,q,t}$) factors. The spillover effect of the currency market factor ($M_{x,t-1}$) on the equity market is specified to enter the equation with one lag. The form of the contagious transmission mechanism is represented by the contemporaneous effect of shocks in the currency market ($\varepsilon_{x,t}$) which is defined as $M_{x,t} = \rho_{m,x} M_{x,t-1} + \varepsilon_{x,t}$ as in equation (2). The choice of a single lag for the spillover and contemporaneous effects for the contagious links is based on a desire to examine the most immediate effects of the shocks in each case.[8] Both spillovers and contagion are modelled across markets as this fits with the characterisation of the East Asian crisis as a crisis which spreads across asset market types. This combination promotes a focus on the potential cross-market contagious linkages. The inclusion of the last term $u_{0,q,t-1}$, controls for the effects of idiosyncratic shocks in the US equity market (the numeraire country) on global equity markets. This variable enters with a lag to allow for the time zone difference between the countries in the Asian time zone (Australia, Indonesia, Korea, Malaysia, and Thailand) and the US, as the equity market data are local market close observations.

The empirical analogue of equation (11) for currency returns ($j = x$) is specified to have the following linear factor structure

$$\begin{aligned} R_{i,x,t} &= \delta_{i,x} W_t + \lambda_{i,x} M_{x,t} + \omega_{i,x} C_{i,t} + \phi_{i,x} u_{i,x,t} + \theta_{i,q,1} M_{q,t-1} \\ &\quad + \gamma_{i,q,0} \varepsilon_{q,t} + \omega_{0,x} C_{0,t} + \phi_{0,x} u_{0,x,t}, \qquad i = 0, 1, \cdots, 5. \end{aligned} \tag{14}$$

As with the equity returns factor equation in (13), the first four factors are the the world (W_t), currency market ($M_{x,t}$), country ($C_{i,t}$) and idiosyncratic ($u_{i,x,t}$) factors. The spillover effect of the equity market factor ($M_{q,t-1}$) on the currency market is specified to enter the equation with one lag. The form of the contagious transmission mechanism from equity to currencies is represented by the contemporaneous effects of shocks in the equity market ($\varepsilon_{q,t}$) which is defined as $M_{q,t} = \rho_{m,q} M_{q,t-1} + \varepsilon_{q,t}$ as in equation (2). Again, this choice is motivated by wanting to focus on the potential cross-market contagious linkages between equity and currency markets. The inclusion of the US country factor ($C_{0,t-1}$) arises from the US being the numeraire country. The parameter $\omega_{0,x}$ is restricted to be the same across all countries to reflect that a shock on bilateral exchange rates from the numeraire country must have the same effect on all country currency markets. See Appendix A for a formal treatment of

[8] Some initial experimentation with lags showed that contemporaneous shocks to capture contagious linkages sufficed.

this condition. The inclusion of the idiosyncratic shocks in the currency market of the numeraire country ($u_{0,x,t-1}$) represents a control variable to allow for the effects of the US on currency markets. The parameter associated with $u_{0,x,t}$, is also restricted to be the same across countries for the same reason as the parameter on $C_{0,t-1}$ is the same across countries. Unlike the time zone issues for equity markets, the numeraire country factor and numeraire currency idiosyncratic factors do not enter with a lag to allow for time zone differences as all of the exchange rates are based on the New York close.

In specifying the dynamics of the latent factors, the full specification in (2) to (4) was initially estimated. However, this led to some instability in the autocorrelation and GARCH parameter estimates suggesting that the initial specification of the model was overparameterised. The final specification of the factor dynamics chosen consists of the world (W_t) and the two market factors ($M_{q,t}, M_{x,t}$) having AR(1) structures with GARCH(1,1) conditional volatilities

$$\begin{array}{rcll} W_t &=& \rho_w W_{t-1} + \nu_t & \\ M_{j,t} &=& \rho_{m,j} M_{j,t-1} + \varepsilon_{j,t}, & j = q, x \\ \nu_t &\sim& N(0, h_{w,t}) & \\ \varepsilon_{j,t} &\sim& N(0, h_{m,j,t}), & j = q, x \\ h_{w,t} &=& 1 - \alpha_w - \beta_w + \alpha_w \nu_{t-1}^2 + \beta_w h_{w,t-1} & \\ h_{m,j,t} &=& 1 - \alpha_{m,j} - \beta_{m,j} + \alpha_{m,j} \varepsilon_{j,t-1}^2 + \beta_{m,j} h_{m,j,t-1}, & j = q, x. \end{array} \tag{15}$$

All of the remaining factors are specified as

$$\begin{array}{rcll} C_{i,t} &\sim& N(0,1), & i = 0, 1, 2, \cdots 5 \\ u_{i,t} &\sim& N(0,1), & i = 0, 1, 2, \cdots 5. \end{array} \tag{16}$$

Based on equation (5), the unconditional volatility structure of the empirical model specified in equations (13) to (16), is summarised in Table 4. This format is used in presenting the empirical results below.

3.3 Estimation Methods

The dynamic latent factor model is estimated using a simulation estimator based on the work of Gourieroux, Monfort and Renault (1993), Duffie and Singleton (1993) and Gallant and Tauchen (1996).[9] This estimator produces consistent estimates and

[9]This estimator is referred to as indirect inference by Gourieroux, Monfort and Renault (1993), simulated GMM by Duffie and Singleton (1993) and efficient method of moments by Gallant and Tauchen (1996). These estimators have the same asymptotic distributions, and for certain specifications of the moment conditions produce the same numerical values. Recent applications include Dai and Singleton (2000) and Dungey, Martin and Pagan (2000) to interest rate factor models, and by Anderson, Benzoni and Lund (2002) to continuous time models of equities.

Table 4:

Unconditional volatility decompositions based on equations (13) to (16).

Factor	Equity Returns $(R_{i,q,t})$	Currency Returns $(R_{i,x,t})$
World	$\delta_{i,q}^2/\left(1-\rho_w^2\right)$	$\delta_{i,q}^2/\left(1-\rho_w^2\right)$
Market	$\lambda_{i,q}^2/\left(1-\rho_{m,q}^2\right)$	$\lambda_{i,x}^2/\left(1-\rho_{m,x}^2\right)$
Country	$\omega_{i,q}^2$	$\omega_{i,x}^2$
Idiosyncratic	$\phi_{i,q}^2$	$\phi_{i,x}^2$
Spillover	$\theta_{i,x,1}^2/\left(1-\rho_{m,x}^2\right)$	$\theta_{i,q,1}^2/\left(1-\rho_{m,q}^2\right)$
Contagion	$\gamma_{i,x,0}^2$	$\gamma_{i,q,0}^2$
Country (numeraire)	$-$	$\omega_{0,x}^2$
Idiosyncratic (numeraire)	τ_i^2	$\phi_{0,x}^2$

under certain conditions achieves asymptotic efficiency. This contrasts with estimates based on either GMM or the Kalman filter which are inconsistent as a result of the nonlinearities arising from the GARCH volatility specification, Gourieroux and Monfort (1994).

The estimation strategy consists of simulating the latent factor model for an initial set of starting parameters to generate a set of simulated returns. The length of the simulated returns is chosen as $N = HT$, where T is the sample size of the actual returns and $H > 0$ is a constant. The simulated returns are then calibrated with the actual returns via a set of moment conditions. The set of moment conditions used in calibrating the model are chosen to capture the empirical characteristics of the data, which, in turn, are used to identify the parameters of the underlying model. This set of moment conditions is discussed in detail in Appendix C, but can be summarized as capturing the contemporaneous correlations amongst returns, as well as the autocorrelations in both the means and the variances of returns.

Let g_t represent a $(M \times 1)$ vector of M moments evaluated using the actual returns. Also define an analogous $(M \times 1)$ vector of M moments, but now evaluated using the simulated data, denoted by v_t. Defining Ψ to represent the set of unknown parameters in the latent factor model, the indirect estimator is obtained as the solution to

$$\widehat{\Psi} = \arg\min_{\Psi} \left[\overline{g} - \overline{v}\right]' \Omega^{-1} \left[\overline{g} - \overline{v}\right], \tag{17}$$

where $\overline{g}$ and $\overline{v}$ are the $(M \times 1)$ vectors of sample means of g_t and v_t respectively. The matrix Ω^{-1} represents the optimal weighting matrix, where Ω is computed as

$$\Omega = \Gamma_0 + \sum\nolimits_{l=1}^{P} \omega_l \left(\Gamma_l + \Gamma_l'\right), \tag{18}$$

for a maximum of P lags, where

$$\Gamma_l = \frac{1}{T} \sum_{t=l+1}^{T} \left(g_t - \overline{g}\right) \left(g_{t-l} - \overline{g}\right)',$$

is the autocovariance matrix at lag l, and

$$\omega_l = 1 - \frac{l}{P+1}, \tag{19}$$

is the Newey-West weight (Gourieroux, Monfort and Renault (1993)). Examples of implementing this type of model with applications to measuring transmissions in financial markets are given in Dungey and Martin (2004).

The objective function in (17) for this problem is minimized using the OPTMUM procedure in GAUSS version 6.0 with numerical gradients. The procedure RNDN is used to obtain normal random numbers to simulate the model. The estimation of the model is carried out with a simulation path of $H = 100$, with $T = 303$ observations, giving a sample size for the simulated data of $N = HT = 30300$ observations. The length of the lag distribution to compute the Newey-West weights in (18) and (19) is set at $P = 5$.

3.4 Empirical Results

The results of estimating the model in (13) to (16) by indirect estimation are presented and analysed in what follows. The focus is on the means by which shocks to the system are transmitted across different asset classes and across geographic borders, and in testing for the significance of those linkages by formally testing for the presence of spillovers and contagion. Volatility decompositions based on the expressions given in Table 4 quantify the relative contributions of spillovers and contagion, while a comparison with the pre-crisis period provides further evidence of the significance of these effects.

3.4.1 Parameter Estimates and Specification Tests

Tables 5 and 6 contain the point estimates of the parameters of the factor model in equations (13) to (16). Standard errors are given in parentheses which are based on the optimal weighting matrix in (18). The standard errors are in general relatively large compared to the corresponding point estimates, suggesting that the model is overparameterised. The approach adopted here is not to undertake an extensive specification search to reduce the dimension of the model, but instead focuses on the rich dynamics of impulse responses and joint specification tests, rather akin to the approach of vector autoregression analysis compared with a Cowles style structural model. An overall test of the model is given by testing the number of overidentifying restrictions. The test statistic is the sample size times the value of the objective function in (17) evaluated at the parameter estimates given in Tables 5 and 6. The test statistic is $303 \times 0.053 = 16.116$. The number of moment conditions is 105 and the number of estimated parameters is 82, yielding 23 overidentifying restrictions. Under the null hypothesis that the model is correctly specified the distribution of the test statistic has an asymptotic chi-squared distribution with degrees of freedom equal to the number of overidentifying restrictions. The p-value of the statistic is 0.850, showing that the model is not rejected at conventional significance levels.

Table 7 contains a range of consistency tests that compare the moments of the auxiliary model using the actual data with the same moments based on the simulated data (Gourieroux, Monfort and Renault (1993, p.111)). Under the null hypothesis that the model is correctly specified the test statistics have an asymptotic chi-squared distribution with degrees of freedom equal to the number of moments. The first test reported is an overall test that there are no differences between any of the 105 moments of the auxiliary model based on actual and simulated returns. The p-value is 0.349, showing that the null is not rejected at conventional significance levels. The next three consistency tests provide a breakdown of the overall test in terms of moments of the auxiliary model that are designed to capture the contemporaneous, autocorrelation and volatility features of the data respectively. In all cases the null hypothesis is not rejected at conventional significance levels.

A further diagnostic of the estimated multi-factor model is given in Table 8 which contains the contemporaneous correlations of the simulated returns amongst the six equity markets, the five currency markets as well as the cross-market correlations. Comparing the correlation matrices of the simulated returns in this table with the correlations based on the actual returns series in Table 1 shows that the estimated model does a very good job at capturing the correlation structure amongst all financial returns.

3.4.2 Dynamics

An important aspect of the transmission of shocks in financial markets is to understand both the strength and duration of the effects of those shocks. To highlight these dynamics, Figures 1 to 3 present the impulse responses for the 11 asset market returns to unit shocks in the global factor, W_t, the currency market factor, $M_{x,t}$, and the equity market factor, $M_{q,t}$. The impulse responses are obtained by simulating the estimated model over the crisis period $10,000$ times and computing the mean of the simulated values for each time horizon. The confidence intervals are also presented, being based on 2 standard deviations of the simulated data.

Table 5:
Indirect parameter estimates of the multi-factor model in equations (13) and (14), with standard errors based on the optimal weighting matrix in parentheses. The value of the objective function in (17) is 0.053.

Country	World (δ)	Market (λ)	Country (ω)	Idios. (ϕ)	Spill (θ)	Cont. (γ)	TZone (τ)
			Equity Markets				
Korea	0.113 (0.374)	-1.593 (10.091)	1.777 (6.141)	1.665 (6.874)	1.399 (3.706)	0.242 (1.065)	-0.064 (0.309)
Indon	0.838 (0.430)	0.329 (2.059)	1.537 (1.959)	0.353 (8.248)	1.436 (3.609)	0.386 (1.626)	-0.543 (0.392)
Thai	0.308 (0.293)	-0.444 (2.861)	0.327 (0.397)	1.571 (0.185)	1.631 (4.189)	-0.042 (0.785)	-0.465 (0.387)
Malay	0.995 (0.609)	-0.605 (3.793)	-0.302 (0.452)	1.751 (0.175)	1.508 (3.790)	0.540 (2.004)	-0.595 (0.458)
Aust	-0.031 (0.129)	-0.311 (1.894)	-0.030 (0.123)	0.177 (2.666)	0.228 (0.538)	0.339 (0.845)	-0.880 (0.512)
US	-0.097 (0.117)	-0.304 (1.815)	0.774 (0.481)	0.655 (0.562)	0.098 (0.322)	0.381 (0.950)	
			Currency Markets				
Korea	-0.250 (0.282)	-0.598 (1.598)	-0.438 (1.464)	1.584 (0.468)	0.843 (5.462)	-0.563 (3.493)	
Indon	-1.445 (0.801)	-0.866 (2.260)	0.213 (0.645)	3.148 (0.511)	1.837 (11.202)	1.409 (9.298)	
Thai	-0.840 (0.395)	-0.234 (0.721)	-1.112 (1.065)	-0.182 (6.646)	0.102 (0.652)	0.217 (1.523)	
Malay	-0.919 (0.518)	0.035 (0.259)	0.722 (0.744)	-0.096 (5.013)	0.251 (1.394)	0.931 (5.962)	
Aust	-0.281 (0.212)	-0.264 (0.764)	0.547 (0.331)	0.075 (2.436)	-0.122 (0.794)	0.256 (1.587)	
US			-0.059 (0.115)	0.264 (0.163)			

Table 6:
Indirect parameter estimates of the multi-factor model in equation (15), with standard errors based on the optimal weighting matrix in parentheses. This Table contains the parameter estimates that control the dynamics of the factors.

Parameter	World	Market - Equity	Market - Currency
α	0.058	0.451	0.171
	(1.926)	(1.064)	(1.199)
β	0.852	0.495	0.822
	(12.195)	(2.894)	(1.343)
ρ	0.060	0.257	0.418
	(0.192)	(0.442)	(0.320)

Table 7:
Consistency tests comparing the moment conditions of the auxiliary model based on actual returns with the same moment conditions using simulated returns. Simulated returns are computed using the point estimates given in Tables 5 and 6 with the length of each simulated series equal to $N = 30300$.

Test	Statistic	Degrees of Freedom	p-value
All	110.056	105	0.349
Contemporaneous	12.792	66	1.000
Autocorrelation	0.766	33	1.000
Volatility	1.766	6	0.940

Table 8:
Correlation matrices of simulated equity and currency returns. The simulated returns are computed using the point estimates given in Tables 5 and 6.

Equity markets

	Korea	Indon	Thai	Malay	Aust	US
Korea	1.000					
Indon	0.250	1.000				
Thai	0.419	0.500	1.000			
Malay	0.407	0.535	0.536	1.000		
Aust	0.294	0.336	0.374	0.445	1.000	
US	0.196	0.046	0.104	0.150	0.223	1.000

Currency markets

	Korea	Indon	Thai	Malay	Aust
Korea	1.000				
Indon	0.202	1.000			
Thai	0.130	0.323	1.000		
Malay	-0.012	0.471	0.470	1.000	
Aust	0.048	0.254	0.373	0.437	1.000

Equity/Currency markets

	Korea	Indon	Thai	Malay	Aust
Korea	-0.118	-0.269	-0.148	-0.326	-0.235
Indon	-0.182	-0.100	-0.229	-0.101	-0.225
Thai	-0.062	-0.177	-0.244	-0.181	-0.201
Malay	-0.127	-0.301	-0.310	-0.388	-0.344
Aust	-0.072	-0.211	-0.108	-0.165	-0.240
US	-0.069	-0.172	-0.088	-0.137	-0.219

Figure 1 reveals that the effects of global factor shocks are statistically significant, as the confidence intervals do not contain zero, but in general quite short-lived, with the impact dissipating after a day. The initial effect on currency markets is in general more substantial than on equity markets across the countries examined, and tends to be associated with a fall in returns in currency markets, and a rise in equity markets. The exception to this is the developed countries, where the initial effect on Australian and US equity markets is negative, and rather small.

In contrast with the short-lived effects of global shocks, the duration of currency market shocks tends to last for about a week with the confidence intervals including zero thereafter. The effects of the currency market shock on currency markets generally results in a fall in returns, although the level of the impact is less than half the original shock. In the case of Malaysia the effect is extremely small, and initially positive, although only marginally significant. The cross-market effect of a currency market shock on equity markets is a rise in equity returns. Most of the countries display a pronounced peak effect, with the maximum impact occurring on the second day, which is where the spillover effects of the shock enter.

The equity market shock produces a less cohesive picture in Figure 3 in terms of duration than did the impulse responses of the currency market shock. This figure shows that an equity market shock results in falls in equity returns for most countries, ranging from quite small falls in Australia and the US, to about one-third of the original shock in Malaysia and Thailand. The confidence intervals show that these effects are statistically significant for the first three to four days but dissipate thereafter. In the case of Indonesia, the equity market shock results in a rise in equity market returns, in contrast to all the other markets. The cross-market effects of the equity market shock into currency markets produces more mixed outcomes. In Korea, the initial effect is negative, but when spillovers impact on the second day a positive peak occurs, and then runs down over the rest of the first week. In Australia, the reverse occurs, with an initial positive reaction to the shock followed by a (small) negative trough on the second day. Indonesia experiences a second day peak, and a greater than one for one positive reaction to the shock. Malaysia and Thailand have a positive reaction to the shock, small in the case of Thailand and relatively larger for Malaysia, but with no second day peak.

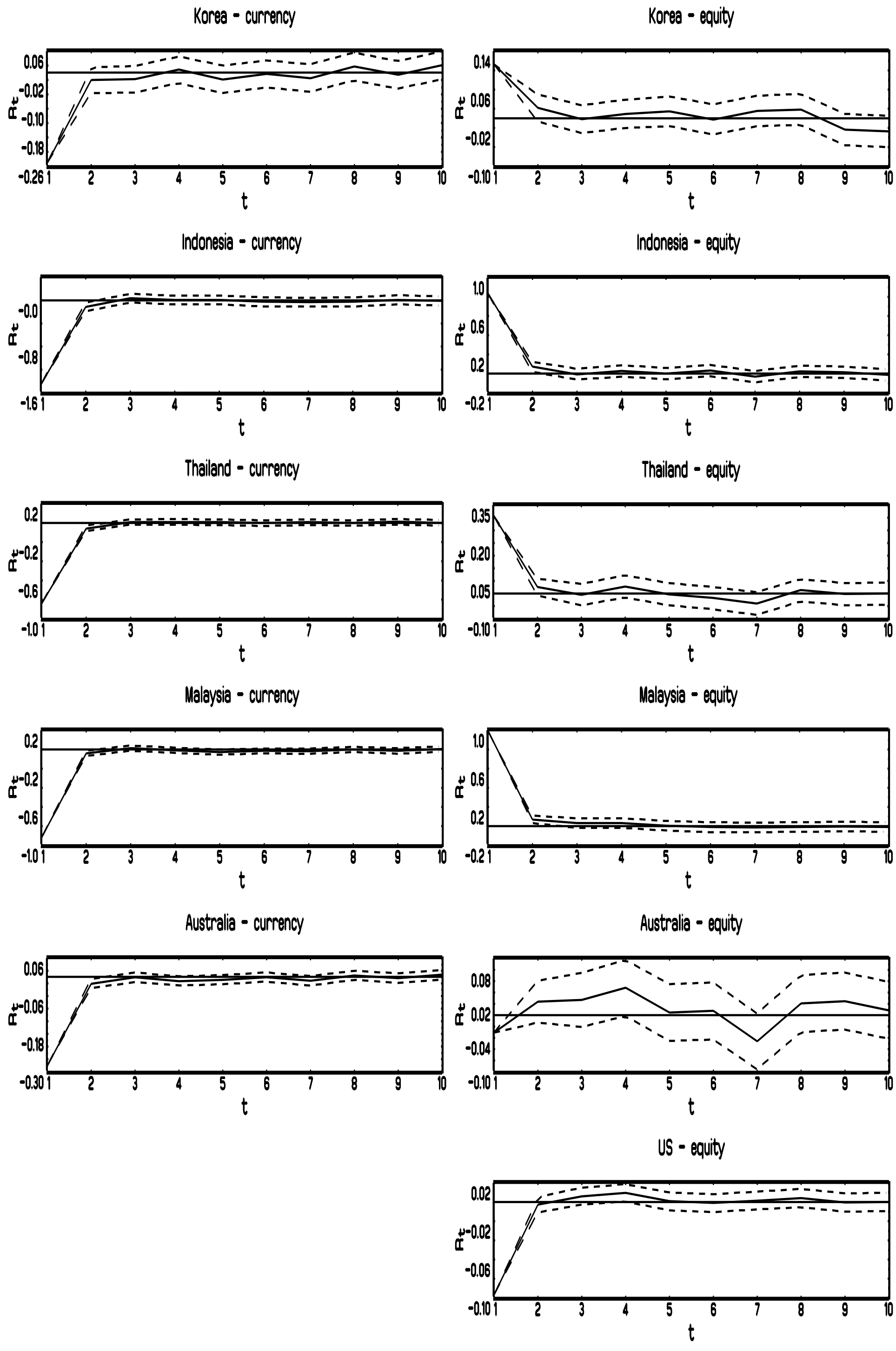

Figure 1: Effects of a one unit shock in the global factor.

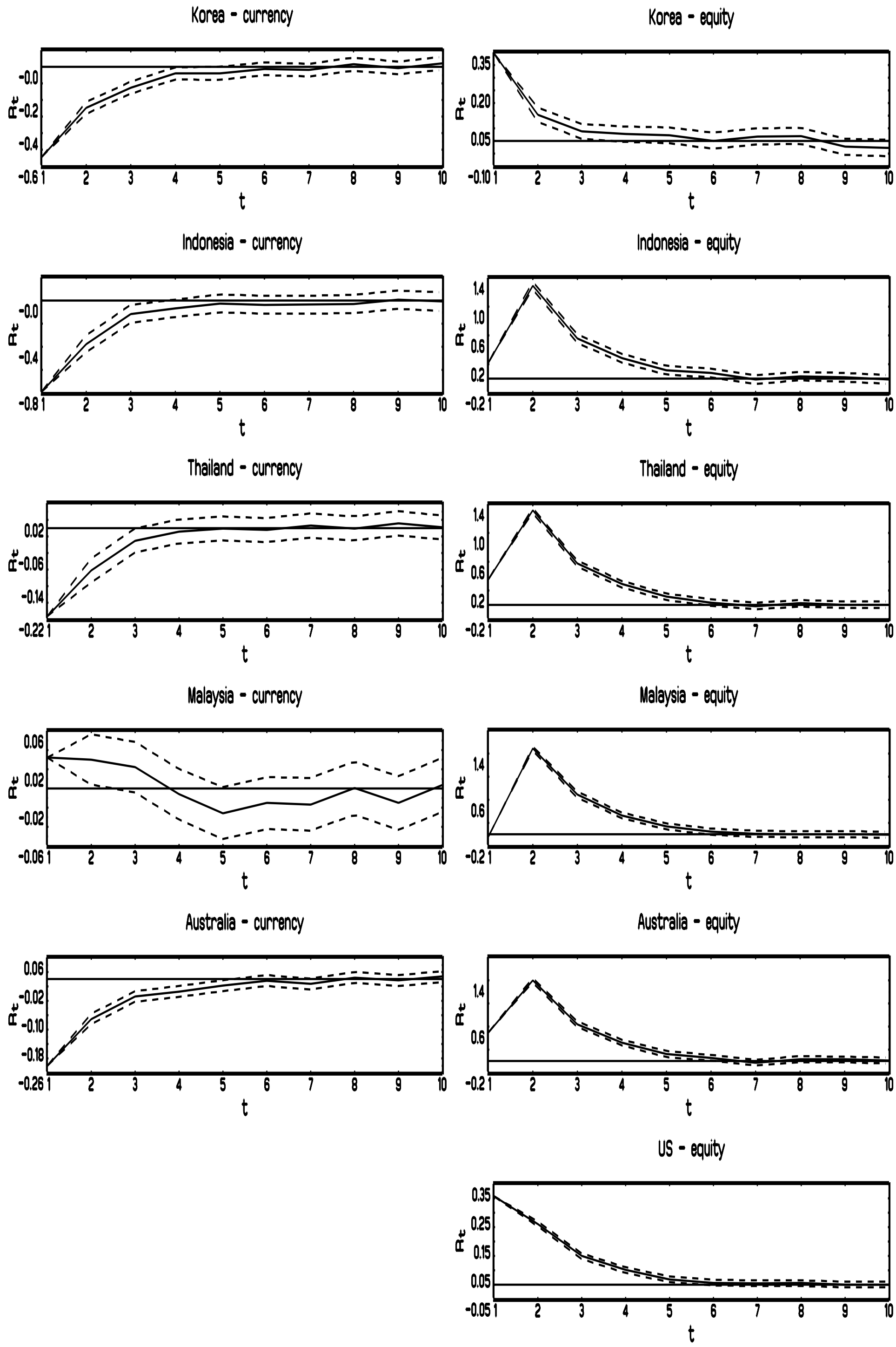

Figure 2: Effects of a one unit shock in the currency market factor.

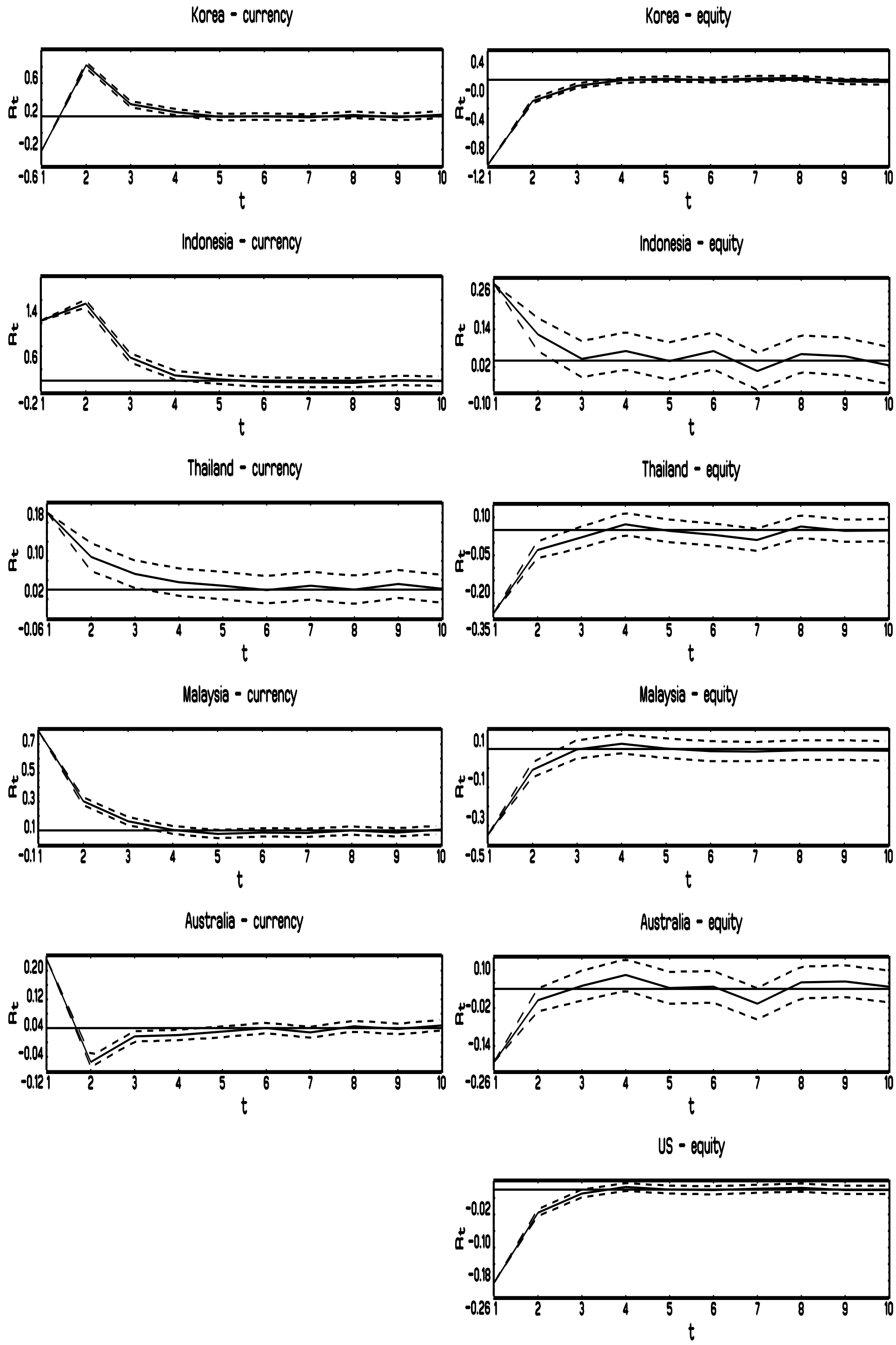

Figure 3: Effects of a one unit shock in the equity market factor.

3.4.3 Tests of Spillovers and Contagion

In presenting the impulse responses in Figures 1 to 3 the effects of the two asset market shocks do not disentangle the relative strengths of contagion and spillover channels. To test the significance of these two channels Table 9 provides the results of a number of specification tests. The tests are based on a likelihood ratio test by comparing the constrained and unconstrained values of the objective function in (17). Under the null, the statistic is asymptotically distributed as χ^2_R, where R is the number of restrictions. The number of restrictions in given in the second last column of Table 9, with the p-values reported in the last column.

The first hypothesis tested in Table 9 is a joint hypothesis of no spillovers and no contagion. The null is easily rejected at standard significance levels. The next two hypotheses focus on the statistical significance of the spillover and contagion channels separately. In both cases the null is rejected at the 5 percent level, although the null of no spillovers is not rejected at the 1 percent level. The results from testing the fourth and fifth hypotheses in Table 9, show that contagion from equity markets to currency markets is statistically significant at the 5 percent level, and that contagion from currency to equity markets is statistically weaker, although still significant at the 10 percent level. The last two hypotheses tested in Table 9 show that contagion is also significant in transmissions to the developed financial markets of the US and Australia, thereby supporting the contention that transmissions to the developed markets were due to more than fundamental linkages.

3.4.4 Variance Decompositions

To gauge the relative size of the contribution of spillovers and contagion to the volatility in asset returns, volatility decompositions are reported in Table 10. This Table shows that volatility in the Korean financial markets is dominated by internal shocks with the combination of country and idiosyncratic shocks being just over 55 percent in the equity market and just over 60 percent in the currency market. Spillovers are relatively important in contributing to volatility in both Korea's currency and equity markets, at just under 20 percent, but, there is very little evidence of contagion contributing to volatility. These results are consistent with the analysis of the weakness of the Korean banking system and deteriorating fundamentals as laying the basis for its crisis, Puri,

Table 9:

Likelihood ratio tests of statistical significance of alternative models.

Hypothesis	Likelihood ratio statistic	Degrees of freedom	p-value
No contagion and no spillovers	63.146	22	0.000
No spillovers	19.897	11	0.047
No contagion	29.057	11	0.002
No contagion from equity markets	16.038	5	0.007
No contagion from currency markets	11.176	6	0.083
No spillovers to Australia and the US	4.736	3	0.192
No contagion to Australia and the US	10.585	3	0.014

Kuan and Maskooki (2002).

Analysis of the turmoil in Indonesian financial markets during the East Asian crisis generally highlights the role of political unrest, but disagrees on the extent of fundamental problems; Kenman (1999) argues that Indonesian fundamentals were sound while Iriana and Sjöholm (2002) point to the role of the larger share of short term debts as a weakness. Due to this relative perceived fundamental strength, Radelet and Sachs (1998) and Goldstein, Kaminsky and Reinhart (2000) have suggested that Indonesia was the country most affected by contagion in this crisis. The volatility decomposition in Table 10 indicates that the measured contagion effect of less than 1 percent for the equity market and about 7 percent for the currency market is much less substantial than the contributions of domestic factors or spillovers. Spillovers contribute about 37 percent to the volatility of Indonesia's equity market and 21 percent to the volatility of it's currency market.

Thailand is often cited as the root shock for the East Asian currency crisis, for example Debelle and Ellis (2005), Fang and Miller (2002), Baig and Goldfajn (1999). This observation is supported by the volatility decomposition in Table 10, which shows that Thai currency volatility is dominated by the country factor, whereas over 90 percent of volatility in the Thai equity markets is due to the combination of idiosyncratic shocks (42 percent) and spillovers (48 percent).

The potential importance of including cross asset market linkages in modelling transmission during crisis periods is illustrated in the case of Malaysia. The decomposition of the volatility of equity market returns shows a substantial (32 percent) contribution of spillovers from currency markets, while the decomposition of the volatility of the currency market returns show a 36 percent contribution from contagion from equity markets.

The most interesting aspects of the developed country results are the importance of shocks in the US financial markets for Australia. In the case of the Australian equity market, over 70 percent of volatility is the result of idiosyncratic shocks originating in the US equity market. This raises the possibility that potential contagious transmissions from Asia to Australia can either operate directly through the impact of shocks in East Asian financial markets on Australian financial markets, or indirectly via the US. This last channel is emphasised by Kaminsky and Reinhart (2002) who argue that the financial markets of developed economies can act as a conduit in the transmission of financial crises, particularly between regional groups.

3.4.5 Comparison with Pre-crisis Period

To examine further the relative strength of contagion during financial crises, it is of interest to compare the crisis results with those that would be obtained for a non-crisis period where contagion was not present. As fixed exchange rate regimes prevailed in three of the four East Asian economies considered here prior to the crisis period of 1997-1998, it is appropriate to concentrate on the equity market characteristics when comparing the pre-crisis period with the crisis period. This focus on equity markets means that it is necessary to limit the structure of the common factor model as the global, market and country specific shocks are now no longer identifiable separately. This suggests that a one factor model is an appropriate specification of equities during the pre-crisis period estimated over the period 1st January 1996 to 31st March 1997. The period between this and the crisis period beginning on 2nd July 1997, is omitted due to debate as to the true beginning of the crisis.

Table 11 shows the observed variances in each of the equity market returns in the pre-crisis and crisis periods in the second and third columns. The fourth column gives the corresponding percentage increase in variance between the two periods. This increase is divided into two components: that due to the increase in volatility of the

Table 10:

Volatility decompositions of asset markets during the crisis period: expressed in percentages.

Factor		Country					
		Korea	Indon.	Thai.	Malay.	Aust.	US
				Equity Markets			
World	W_t	0.118	11.820	1.602	13.026	0.088	0.731
Market	$M_{q,t}$	25.125	1.939	3.543	5.134	9.587	7.682
Country	$C_{i,t}$	29.198	39.656	1.794	1.195	0.085	46.370
Idiosyncratic	$u_{i,q,t}$	25.618	2.096	41.511	40.231	2.905	33.203
Spillovers	$M_{x,t-1}$	19.363	37.043	47.884	31.947	5.147	0.796
Contagion	$\varepsilon_{x,t}$	0.541	2.596	0.030	3.821	10.591	11.218
Idios. (US)	$u_{0,q,t-1}$	0.038	4.941	3.637	4.646	71.595	n.a.
Total		100.000	100.000	100.000	100.000	100.000	100.000
				Currency Markets			
World	W_t	1.408	10.972	32.533	35.382	12.617	n.a.
Market	$M_{x,t}$	9.737	4.757	3.048	0.063	13.548	n.a.
Country	$C_{i,t}$	4.31	0.237	56.791	21.744	47.892	n.a.
Idiosyncratic	$u_{i,x,t}$	56.419	51.850	1.526	0.387	0.904	n.a.
Spillovers	$M_{q,t-1}$	19.360	21.407	0.581	3.197	2.858	n.a.
Contagion	$\varepsilon_{q,t}$	7.124	10.395	2.170	36.177	10.511	n.a.
Country (US)	$C_{0,t}$	0.078	0.018	0.160	0.146	0.557	n.a.
Idios. (US)	$u_{0,x,t}$	1.564	0.364	3.191	2.903	11.112	n.a.
Total		100.000	100.000	100.000	100.000	100.000	n.a.

Table 11:

Contributions to the increase in equity returns volatility from pre-crisis to crisis period. Pre-crisis period 1st January 1996 to 31st March 1997, crisis period 2nd July 1997 to 31st August 1998.

Country	Variance			Contributions to Variance	
	Pre-crisis	Crisis	% change	Common and Idiosyncratic	Contagion and Spillovers
Korea	1.701	1.433	500.756	381.180	119.576
Indonesia	0.878	10.234	840.058	468.317	371.741
Thailand	2.003	8.254	241.223	77.727	163.495
Malaysia	0.603	6.833	1430.426	883.028	547.398
Australia	0.508	9.229	123.292	88.242	35.049
US	0.611	1.134	134.563	106.245	28.318

common and idiosyncratic factors (column 5), and that due to contagion and spillovers (column 6).[10]

Table 11 clearly shows that there is a much higher increase in variance experienced in the developing markets than in the developed markets of Australia and the US. Malaysia (1430%) experiences the greatest increase in volatility in equity returns and Thailand (241%) the least in the East Asian countries. The contribution of contagion and spillovers to this increase in volatility in both countries is over 60 percent of the total observed increase; that is, the increase in volatility between the non-crisis and crisis periods not primarily due to higher volatility in the common and idiosyncratic factors. This contrasts with the US, Korea and Australia, where the increase in volatility is primarily due to common and idiosyncratic factors, with less than 30 percent of the increase due to contagion effects. Indonesia is between these two extremes, with 44 percent of the increase in volatility attributable to contagion.

The results in Table 11 throw further light on those reported for the crisis period

[10]This decomposition of the change in variance between pre-crisis and crisis periods which isolates increases in volatility arising from either the common factors or the idiosyncratic factors, is similar to the correction adopted by Forbes and Rigobon (2002) in testing for contagion, see also Loretan and English (2000).

in Tables 10 and 9 in the previous section. In the crisis period contagion and spillovers contributed a significant, although sometimes small, component to the volatility of returns. Comparisons with the pre-crisis period show that contagion and spillovers potentially contribute a substantial amount to the increase in volatility observed between the two periods.

4 Conclusions

Empirical work on linkages between financial assets during crises tends to focus on modelling one asset market at a time. This paper showed how a dynamic latent factor framework can be used to model a range of potential linkages that connect asset markets across national boundaries during financial crises. Both spillovers and contagion were modelled as well as a range of common shocks and idiosyncratic shocks. Spillovers were defined as cross-market linkages at time t of shocks which occurred at time $t-1$, while contagion referred to residual shocks contemporaneously transmitted. A special feature of these factors was that they were latent, being identified by the comovements of asset returns within and across classes of financial markets.

The latent factor model was applied to assessing the relative strengths of spillovers and contagion between currency and equity markets in the East Asian crisis of 1997-98. The main empirical result was to highlight the importance of cross-market linkages in contributing to the volatility in both asset returns. Spillover effects between markets were relatively larger than contagion effects, although both transmission channels were statistically significant.

The results revealed that for many of the financial markets in East Asia, over half of the observed volatility was the result of either country factors or idiosyncratic factors, lending some credence to the argument put by Karolyi (2003) that perhaps the emphasis on reform of international financial architecture is misplaced, and attention should rather be paid to national issues. However, a comparison with results based on pre-crisis data emphasised the important role which contagion and spillovers can play in increasing the volatility of returns between non-crisis and crisis periods. Finally, the results showed that the US financial markets can act as a conduit in transmitting crises across countries, implying particularly for Australia that there were both direct and indirect channels for contagion from the East Asian financial crisis.

The empirical results of this paper provide strong support for modelling currency and equity markets simultaneously during financial crises, and suggest that studies which focus on currency and equity markets separately are potentially misspecified. The results also highlight the need for the debate on identifying the causes of financial crises to be broadened to examine spillovers and contagion across country asset markets, as well as across national borders.

A Derivation of No-Arbitrage Condition

Consider a model of three currencies, $1, 2$ and 3, where there are three potential exchange rates between those countries, represented as $R_{1,2,t}$, $R_{1,3,t}$ and $R_{2,3,t}$. With the assumption of no-arbitrage this appendix shows that a simple linear latent factor model of the three exchange rates can be expressed using two exchange rates against a common numeraire currency. The parameter on the country effect for each country involved in the exchange rate must be the same in each exchange rate in which it is involved. The parameter estimates for the remaining cross-rate can be backed out from the other two expressions. To see this consider a simplified four factor version of equation (1) containing a common world factor, W_t, country specific factors relating to each of the countries in the bilateral exchange rate, $C_{i,t}$ and $C_{j,t}$, each of which have potentially different coefficients and the idiosyncratic factor, $u_{i,j,t}$. The three exchange rates can be expressed as

$$R_{1,2,t} = \delta_{1,2}W_t + \omega_1 C_{1,t} + \omega_2 C_{2,t} + \phi_{1,2}u_{1,2,t} \quad (20)$$

$$R_{1,3,t} = \delta_{1,3}W_t + \omega_3 C_{1,t} + \omega_4 C_{3,t} + \phi_{1,3}u_{1,3,t} \quad (21)$$

$$R_{2,3,t} = \delta_{2,3}W_t + \omega_5 C_{2,t} + \omega_6 C_{3,t} + \phi_{2,3}u_{2,3,t}. \quad (22)$$

Assuming the exchange rates are expressed in natural logarithms and that any problems due to Jensen's inequality are insubstantial, arbitrage in foreign exchange markets results in the condition that $R_{2,3,t} = R_{1,2,t} - R_{1,3,t}$. The equivalent expression using equations (20) to (21) above is

$$\delta_{2,3}W_t + \omega_5 C_{2,t} + \omega_6 C_{3,t} + \phi_{2,3}u_{2,3,t} = \delta_{1,2}W_t + \omega_1 C_{1,t} + \omega_2 C_{2,t} + \phi_{1,2}u_{1,2,t} - \left(\delta_{1,3}W_t + \omega_3 C_{1,t} + \omega_4 C_{3,t} + \phi_{1,3}u_{1,3,t}\right). \quad (23)$$

Equating the coefficients on each side of equation (23) gives the following restrictions

$$\delta_{2,3} = \delta_{1,2} - \delta_{1,3}; \omega_5 = \omega_2; \omega_6 = -\omega_4; \omega_1 = \omega_3. \quad (24)$$

It is apparent that the coefficient on any of the country factors remains constant regardless of which exchange rate it is involved in, and that the coefficient on the world factor for the cross rate is simply backed out from the coefficients on the exchange rates against a common numeraire currency. This implies that it is simple to determine the parameters on the cross rate in equation (22) by estimating equations (20) and (21) and using equation (24) to estimate the remaining equation (22). See also Dungey (1999).

B Data Sources

Data are daily sourced from Thomson Financial Datastream with the following codes being correct on September 2000. The exchange rates are measured at a single point in time in New York, whereas equity prices are the domestic closing values. All data are dated on the same calendar day, following Eun and Shim (1989) and Bae, Karolyi and Stulz (2000).

Country	Exchange Rate against USD	Equity Index
US	-	DJINDUS
Korea	KOUSDSP	KORCOMP
Indonesia	USINDON	JAKCOMP
Thailand	USTHAIB	BNGKSET
Malaysia	MYUSDSP	KLPCOMP
Australia	AUSTRUS	ALLORDS

C Moment Specifications

The set of moments used in the simulation procedure to estimate the unknown parameters is designed to capture the key empirical characteristics of the data. Let the set of 6 equity returns and 5 currency returns be summarized as:

$$y_t = \{R_{0,q,t}, R_{1,q,t}, ..., R_{5,q,t}, R_{1,x,t}, R_{2,x,t}, ..., R_{5,x,t}\}, \quad (25)$$

where $R_{i,q,t}$ and $R_{i,x,t}$ are the demeaned equity and currency returns respectively. The auxiliary model consists of four phases. The initial phase it to compute the three largest principal components from an eigen decomposition of the correlation matrix of the 11 asset returns. These three components can be thought of as proxy variables for the world and two market factors, which are used to construct a parsimonious set of moment conditions.[11]

The second phase consists of specifying a set of moment conditions to identify the 19 parameters representing the dynamics in the means of the asset returns: the spillover parameters $\{\theta_{0,q,1}, \theta_{1,q,1}..\theta_{5,q,1}, \theta_{1,x,1}, \theta_{2,x,1}...\theta_{5,x,1}\}$, the time-zone parameters $\{\tau_1, \tau_2, ..., \tau_5\}$ and the autocorrelation parameters underlying the factors $\left\{\rho_w, \rho_{m,q}, \rho_{m,x}\right\}$. These moments are obtained by regressing each of the 11 asset returns on the lagged values of the three principal components and defining

$$g_t^1 = \{v_{1,t} \otimes z_{t-1}; v_{2,t} \otimes z_{t-1}; ...; v_{11,t} \otimes z_{t-1}\},$$

where $v_{i,t}$ $i = 1, 2, ..., 11$ are the residuals from the dynamic regressions and z_{t-1} is a (1×3) vector of the lagged values of the three principal components. Taking the sample average of these moments across all observations yields 33 moments.

The phase consists of specifying a set of moments based on the unique set of variances and covariances of the residuals from the dynamic regression equations obtained in the second phase. Defining the (1×66) vector at time t

$$g_t^2 = \{v_{i,t}v_{j,t}; i \geq j\}. \quad (26)$$

and taking the sample average across all observations, yields 11 variances and 55 covariances to capture the second moments of the data. These moments are used to

[11]The three principal components are biased estimates of the world and two market factors as they are based on an unconditional correlation matrix which does not take into the time-varying volatility underlying asset returns. However, they provide a suitable basis for constructing a general auxiliary model which is used to derive the indirect parameter estimates which are consistent.

identify the 57 parameters representing the contemporaneous correlations amongst the asset returns: the world loading parameters

$$\{\delta_{0,q}, \delta_{1,q}, ..., \delta_{5,q}, \delta_{1,x}, \delta_{2,x}, ..., \delta_{5,x}\},$$

the market factor parameters

$$\{\lambda_{0,q}, \lambda_{1,q}, ..., \lambda_{5,q}, \lambda_{1,x}, \lambda_{2,x}, ..., \lambda_{5,x}\},$$

the country factor parameters

$$\{\omega_{0,q}, \omega_{1,q}, ..., \omega_{5,q}, \omega_{0,x}, \omega_{1,x}, ..., \omega_{5,x}\},$$

the parameters associated with the idiosyncratic terms

$$\{\phi_{0,q}, \phi_{1,q}, ..., \phi_{5,q}, \phi_{1,x}, ..., \phi_{5,x}\},$$

and the contagion parameters

$$\{\gamma_{0,q,0}, \gamma_{1,q,0}, ..., \gamma_{5,q,0}, \gamma_{1,x,0}, \gamma_{2,x,0}, ..., \gamma_{5,x,0}\}.$$

The final phase in specifying the auxiliary model is to identify the conditional variance properties of the asset returns and hence to identify the 6 GARCH parameters in the model

$$\{\alpha_w, \alpha_q, \alpha_x, \beta_w, \beta_q, \beta_x\}.$$

The set of moment conditions chosen are the first and second order autocorrelation coefficients of the squares of the changes in the three principal components (Diebold and Nerlove (1989)). Defining the (1×6) vector at time t

$$g_t^3 = \{\xi_{1,t}^2\xi_{1,t-1}^2; \xi_{1,t}^2\xi_{1,t-2}^2; \xi_{2,t}^2\xi_{2,t-1}^2; \xi_{2,t}^2\xi_{2,t-2}^2; \xi_{3,t}^2\xi_{3,t-1}^2; \xi_{3,t}^2\xi_{3,t-2}^2\}, \quad (27)$$

where $\xi_{i,t}^2$ represents the standardised squared value of the change in the i^{th} principal component. Taking the sample average of g_t^3 yields a further 6 moment conditions.

Grouping all components of the auxiliary model together as

$$g_t = \{g_t^1, g_t^2, g_t^3\}, \quad (28)$$

and taking the sample average, yields $33 + 66 + 6 = 105$ moment conditions in total to identify the 82 unknown parameters in the model.

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