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Empirical modelling of contagion: a review of methodologies

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1. Introduction

There is now a reasonably large body of empirical work testing for the existence of contagion during financial crises. A range of different methodologies are in use, making it difficult to assess the evidence for and against contagion, and particularly its significance in transmitting crises between countries. The origins of current empirical studies of contagion stem from Sharpe (1964) and Grubel and Fadner (1971), and more recently from King and Wadhwani (1990), Engle *et al*. (1990) and Bekaert and Hodrick (1992).‖

The aim of the present paper is to provide a unifying framework to highlight the key similarities and differences between the various approaches. For an overview of the literature see Dornbusch *et al*. (2000) and Pericoli and Sbracia (2003). The proposed framework is based on a latent factor structure which forms the basis of the models of Dungey and Martin (2001), Corsetti *et al*. (2001, 2003) and Bekaert *et al*. (2005). This framework is used to compare directly the correlation analysis approach popularized in this literature by Forbes and Rigobon (2002), the VAR approach of Favero and Giavazzi (2002), the probability model of Eichengreen *et al*. (1995, 1996) and the co-exceedance approach of Bae *et al*. (2003).

An important outcome of this paper is that differences in the definitions used to test for contagion are minor and under certain conditions are even equivalent. In particular, all definitions are interpreted as working from the same model, with the differences stemming from the amount of information used in the data to detect contagion. Interpreting the approaches in this way provides a natural ordering of models across the information spectrum with some models representing full information methods and others representing partial information methods.

The paper proceeds as follows. In section 2 a framework is developed to model the interdependence between asset returns in a non-crisis environment. This framework is augmented in section 3 to give a model which includes an avenue for contagion during a crisis. The relationship between this model and the bivariate correlation tests for contagion of Forbes and Rigobon is discussed in section 4. This section also includes a number of extensions of the original Forbes and Rigobon approach, as well as its relationship with the approaches of Favero and Giavazzi (2002), Eichengreen *et al*. (1995, 1996) and Bae *et al*. (2003). An empirical example comparing the various contagion tests is contained in section 5. The results show that the Forbes and Rigobon adjusted correlation test is a conservative test, whereas the contagion test of Favero and Giavazzi tends to reject the null of no contagion too easily. The remaining tests investigated yield results falling within these two extremes. Concluding comments are given in section 6 together with a number

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‖As this paper focuses on empirical models of contagion it does not discuss the corresponding theoretical literature and more generally the literature on financial crises. For examples of theoretical models of contagion see Allen and Gale (2000), Calvo and Mendoza (2000), Kyle and Xiong (2001), Chue (2002), Kiyotaki and Moore (2002) and Kodres and Pritsker (2002). The literature on financial crises is overviewed in Flood and Marion (1998).

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of suggestions for future research that encompass both theoretical and empirical issues.

2. A model of interdependence

Before developing a model of contagion, a model of interdependence of asset markets during non-crisis periods is specified as a latent factor model of asset returns. The model has its origins in the factor models in finance based on arbitrage pricing theory for example, where asset returns are determined by a set of common factors representing non-diversifiable risk and a set of idiosyncratic factors representing diversifiable risk (Sharpe 1964, Solnik 1974). Similar latent factor models of contagion are used by Corsetti *et al.* (2003, 2001), Dungey and Martin (2001), Dungey *et al.* (2005b), Forbes and Rigobon (2002) and Bekaert *et al.* (2005).

To simplify the analysis, the number of assets considered is three. Extending the model to N assets or asset classes is straightforward. Let the returns of three assets during a non-crisis period be defined as

$$\{x_{1,t}, x_{2,t}, x_{3,t}\}. \tag{1}$$

All returns are assumed to have zero means. The returns could be on currencies, or national equity markets, or a combination of currency and equity returns in a particular country or across countries.† The following trivariate factor model is assumed to summarize the dynamics of the three processes during a period of tranquility

$$x_{i,t} = \lambda_i w_t + \delta_i u_{i,t}, \quad i = 1, 2, 3. \tag{2}$$

The variable w_t represents common shocks that impact upon all asset returns with loadings λ_i. These shocks could represent financial shocks arising from changes to the risk aversion of international investors, or changes in world endowments (Mahieu and Schotman 1994, Cizeau *et al.* 2001, Rigobon 2003b). In general, w_t represents market fundamentals which determine the average level of asset returns across international markets during 'normal', that is, tranquil, times. This variable is commonly referred to as a world factor, which may or may not be observed.‡ For expositional purposes, the world factor is assumed to be a latent stochastic process with zero mean and unit variance

$$w_t \sim (0, 1). \tag{3}$$

The properties of this factor are extended below to capture richer dynamics including both autocorrelation and time-varying volatility. The terms $u_{i,t}$ in equation (2) are idiosyncratic factors that are unique to a specific asset market. The contribution of idiosyncratic shocks to the volatility of asset returns is determined by the loadings $\delta_i > 0$. These factors are also assumed to be stochastic processes with zero mean and unit variance

$$u_{i,t} \sim (0, 1). \tag{4}$$

To complete the specification of the model, all factors are assumed to be independent

$$E\left[u_{i,t}u_{j,t}\right] = 0, \quad \forall i \neq j, \tag{5}$$

$$E\left[u_{i,t}w_t\right] = 0, \quad \forall i. \tag{6}$$

To highlight the interrelationships amongst the three asset returns in (2) during a non-crisis period, the covariances are given by

$$E\left[x_{i,t}x_{j,t}\right] = \lambda_i\lambda_j, \quad \forall i \neq j, \tag{7}$$

whilst the variances are

$$E\left[x_{i,t}^2\right] = \lambda_i^2 + \delta_i^2, \quad \forall i. \tag{8}$$

Expression (7) shows that any dependence between asset returns is solely the result of the influence of common shocks arising from w_t, which simultaneously impact upon all markets. Setting

$$\lambda_1 = \lambda_2 = \lambda_3 = 0, \tag{9}$$

results in independent asset markets with all movements determined by the idiosyncratic shocks, $u_{i,t}$.§ The identifying assumption used by Mahieu and Schotman (1994) in a similar problem is to set $\lambda_i\lambda_j$ to a constant value, L, for all $i \neq j$.

3. An empirical model of contagion

In this paper contagion is represented by the contemporaneous transmission of local shocks to another country or market after conditioning on common factors that exist over a non-crisis period, given by w_t in equation (2). This definition is consistent with that of Masson (1999a, b, c), who decomposes shocks to asset markets into common spillovers, which result from some identifiable channel, and contagion. As shown below this definition is also consistent with that of other approaches, such as Forbes and Rigobon (2002), where contagion is represented by an increase in correlation during periods of crisis.

The first model discussed is based on the factor structure developed by Dungey *et al.* (2002, 2005b). Consider the case of contagion from country 1 to country 2. The factor model in (2) is now augmented as follows

$$\begin{aligned} y_{1,t} &= \lambda_1 w_t + \delta_1 u_{1,t}, \\ y_{2,t} &= \lambda_2 w_t + \delta_2 u_{2,t} + \gamma u_{1,t}, \\ y_{3,t} &= \lambda_3 w_t + \delta_3 u_{3,t}, \end{aligned} \tag{10}$$

†See, for example, Granger *et al.* (2000), Hartmann *et al.* (2004) and Bekaert *et al.* (2005), who model the interactions between asset classes.

‡The model outlined here can be extended to allow for a richer set of factors, including observed fundamentals (Eichengreen *et al.* 1995, 1996), trade linkages (Glick and Rose 1999, Pesaran and Pick 2003), financial flows (Van Rijckeghem and Weder 2001), geographical distance (Bayoumi *et al.* 2003) and Fama-French factors (Flood and Rose 2005).

§Of course, just two of the restrictions in (7) are sufficient for independence of asset markets.

where the $x_{i,t}$ in (2) are replaced by $y_{i,t}$ to signify demeaned asset returns during the crisis period. The expression for $y_{2,t}$ now contains a contagious transmission channel as represented by local shocks from the asset market in country 1, with its impact measured by the parameter γ. The fundamental aim of all empirical models of contagion is to test the statistical significance of the parameter γ.†

3.1. Bivariate testing

Bivariate tests of contagion focus on changes in the volatility of pairs of asset returns. From (10), the covariance between the asset returns of countries 1 and 2 during the crisis is

$$E\left[y_{1,t}y_{2,t}\right] = \lambda_1\lambda_2 + \gamma\delta_1. \tag{11}$$

Comparing this expression with the covariance for the non-crisis period in (7) shows that the change in the covariance between the two periods is

$$E\left[y_{1,t}y_{2,t}\right] - E\left[x_{1,t}x_{2,t}\right] = \gamma\delta_1. \tag{12}$$

If $\gamma > 0$, there is an increase in the covariance of asset returns during the crisis period as $\delta_1 > 0$ by assumption. This is usually the situation observed in crisis data. However, it is possible for $\gamma < 0$, in which case there is a reduction in the covariance. Both situations are valid as both represent evidence of contagion via the impact of shocks in (10). Hence a test of contagion is given by testing the restriction

$$\gamma = 0, \tag{13}$$

in the factor model in equation (10). This is the approach adopted by Dungey *et al.* (2002, 2003a, 2005b) and Dungey and Martin (2004).‡

An alternative way to construct a test of contagion is to use the volatility expression for $y_{2,t}$, which is given by

$$E\left[y_{2,t}^2\right] = \lambda_2^2 + \delta_2^2 + \gamma^2. \tag{14}$$

Comparing this expression with (8) shows that the change in volatility over the two periods is solely attributed to the presence of contagion

$$E\left[y_{2,t}^2\right] - E\left[x_{2,t}^2\right] = \gamma^2. \tag{15}$$

Thus, the contagion test based on (13) can be interpreted as a test of whether there is an increase in volatility. Expression (14) suggests that a useful description of the volatility of $y_{2,t}$ is to decompose the effects of shocks into common, idiosyncratic and contagion respectively as follows

$$\frac{\lambda_2^2}{\lambda_2^2 + \delta_2^2 + \gamma^2}, \quad \frac{\delta_2^2}{\lambda_2^2 + \delta_2^2 + \gamma^2}, \quad \frac{\gamma^2}{\lambda_2^2 + \delta_2^2 + \gamma^2}. \tag{16}$$

This decomposition provides a descriptive measure of the relative strength of contagion in contributing to the volatility of returns during a crisis period. As before, the strength of contagion is determined by the parameter γ, which can be tested formally.

3.2. Multivariate testing

The test for contagion presented so far is a test for contagion from country 1 to country 2. However, it is possible to test for contagion in many directions provided that there are sufficient moment conditions to identify the unknown parameters. For example, (10) can be extended as

$$\begin{aligned} y_{1,t} &= \lambda_1 w_t + \delta_1 u_{1,t} + \gamma_{1,2}u_{2,t} + \gamma_{1,3}u_{3,t}, \\ y_{2,t} &= \lambda_2 w_t + \delta_2 u_{2,t} + \gamma_{2,1}u_{1,t} + \gamma_{2,3}u_{3,t}, \\ y_{3,t} &= \lambda_3 w_t + \delta_3 u_{3,t} + \gamma_{3,1}u_{1,t} + \gamma_{3,2}u_{2,t}, \end{aligned} \tag{17}$$

or more succinctly

$$y_{i,t} = \lambda_i w_t + \delta_i u_{i,t} + \sum_{j=1, j\neq i}^{3} \gamma_{i,j}u_{j,t}, \quad i = 1, 2, 3. \tag{18}$$

The theoretical variances and covariances are an extension of the expressions given in (14) and (11) respectively. For example, the variance of the returns of country 1 is

$$E\left[y_{1,t}^2\right] = \lambda_1^2 + \delta_1^2 + \gamma_{1,2}^2 + \gamma_{1,3}^2, \tag{19}$$

whereas the covariance of asset returns between countries 1 and 2 is

$$E\left[y_{1,t}y_{2,t}\right] = \lambda_1\lambda_2 + \delta_1\gamma_{2,1} + \delta_2\gamma_{1,2} + \gamma_{1,3}\gamma_{2,3}. \tag{20}$$

In this case there are 6 parameters, $\gamma_{i,j}$, controlling the strength of contagion across all asset markets. This model, by itself, is unidentified as there are 12 unknown parameters. However, by combining the empirical moments of the variance–covariance matrix during the crisis period, 6 moments, with the empirical moments from the variance–covariance matrix of the non-crisis period, another 6 moments, gives 12 empirical moments in total which can be used to estimate the 12 unknown parameters by the generalized method of moments (GMM).

A joint test of contagion, using the factor models in (2) and (17), can be achieved by comparing the objective function from the unconstrained model, q_u, with the value obtained from estimating the constrained model, q_c, where the contagion parameters are set to zero. As the unconstrained model is just identified in this case, $q_u = 0$, the test is simply a test that under the null hypothesis of no contagion

$$H_0 : q_c = 0, \tag{21}$$

which is distributed asymptotically as χ^2 with 6 degrees of freedom under the null. As before, the test of

†An important assumption underlying (10) is that the common shock (w_t) and idiosyncratic shocks ($u_{i,t}$) have the same impact during the crisis period as they have during the non-crisis period. This assumption of no structural break is discussed in section 3.3.
‡Most concern seems to centre on the case where $\gamma > 0$, that is where contagion is associated with a rise in volatility. The existing tests can be characterized as testing the null hypothesis of $\gamma = 0$ against either a two-sided alternative or a one-sided alternative.

contagion can be interpreted as testing for changes in both variances and covariances.

3.3. *Structural breaks*

The model given by equations (2) and (18) is based on the assumption that the increase in volatility during the crisis period is solely generated by contagion, that is, $\gamma_{i,j} \neq 0, \forall i,j$. However, another scenario is that there is a general increase in volatility without any contagion; denoted as increased interdependence by Forbes and Rigobon (2002). This would arise if either the world loadings (λ_i) change, or idiosyncratic loadings (δ_i) change, or a combination of the two. The former would be representative of a general increase in volatility across all asset markets brought about, for example, by an increase in the risk aversion of international investors. The latter would arise from increases in the shocks of (some) individual asset markets which are entirely specific to those markets and thus independent of other asset markets.

To allow for structural breaks in the underlying relationships the number of contagious linkages that can be entertained needs to be restricted. In the case where changes in the idiosyncratic shocks are allowed across the sample periods in all $N = 3$ asset markets, equation (18) becomes

$$y_{i,t} = \lambda_i w_t + \delta_{y,i} u_{i,t} + \sum_{j=1, j\neq i}^{3} \gamma_{i,j} u_{j,t}, \tag{22}$$

where $\delta_{y,i} \neq \delta_i$ are the idiosyncratic parameters during the crisis period. Bekaert *et al.* (2005) adopt a different strategy for modelling structural breaks by specifying time varying factor loadings.

The number of world and idiosyncratic parameters now increases to $3N$. Because the model is still block-recursive, there are just $N(N+1)/2$ empirical moments from the crisis period available to identify the contagion parameters ($\gamma_{i,j}$) and the structural break parameters ($\delta_{y,i}$). This means that there are $N(N+1)/2 - N = N(N-1)/2$ excess moments to identify contagion channels.

Extending the model to allow for structural breaks in both common and idiosyncratic factors in all N asset markets, increases the number of world and idiosyncratic parameters to $4N$, now yielding $N(N+1)/2 - 2N = N(N-3)/2$ excess moments to identify contagion channels in the crisis period. For a trivariate model ($N = 3$) that allows for all potential structural breaks in common and idiosyncratic factors, no contagion channels can be tested as the model is just identified. Extending the model to $N = 4$ assets allows for $N(N-3)/2 = 2$ potential contagion channels. Further extending the model to $N = 6$ assets means that the number of contagion channels that can be tested increases to $N(N-3)/2 = 9$.

3.4. *Using just crisis data*

Identification of the unknown parameters in the factor model framework discussed above is based on using information from both non-crisis and crisis periods. For certain asset markets it may be problematic to use non-crisis data to obtain empirical moments to identify unknown parameters. An example being the move from fixed to floating exchange rate regimes during the East Asian currency crisis. However, it is nonetheless possible to identify the model using just crisis period data, provided that the number of asset returns exceeds 3 and a limited number of contagious links are entertained. For example, for $N = 4$ asset returns, there are 10 unique empirical moments from the variance–covariance matrix using crisis data. Specifying the factor model in (2) for $N = 4$ assets means that there are 4 world parameters and 4 idiosyncratic parameters. This implies that 2 contagious links can be specified and identified.

3.5. *Autoregressive and heteroskedastic dynamics*

Given that an important feature of financial returns during crises is that they exhibit high volatility, models which do not incorporate this feature are potentially misspecified. This suggests that the framework developed so far be extended to allow for a range of dynamics.† Four broad avenues are possible. The first consists of including lagged values of the returns in the system. When the number of assets being studied is large, this approach can give rise to a large number of unknown parameters, thereby making estimation difficult. The second approach is to capture the dynamics through lags in the common factor, w_t. This provides a more parsimonious representation of the system's dynamics as a result of a set of cross equation restrictions arising naturally from the factor structure. A third approach is to specify autoregressive representations for the idiosyncratic factors, $u_{i,t}$. The specification of dynamics on all of the factors yields a state-space representation which can be estimated using a Kalman filter, see for example Mody and Taylor (2003).

A fourth approach for specifying dynamics, which is potentially more important for models of asset returns than dynamics in the mean, is the specification of dynamics in the variance. This is especially true in models of contagion as increases in volatility are symptomatic of crises.‡ A common way to capture this phenomenon is to include a *GARCH* structure on the factors. This

†This implies that methods based on principal components, such as Kaminsky and Reinhart (2001), which assume constant covariance matrices are inappropriate to model financial crises.

‡A further approach is by Jeanne and Masson (2000) who allow for a Markovian switching structure to incorporate the multiple equilibria features of theoretical contagion models.

approach is adopted by Dungey *et al.* (2003a, 2005b), Dungey and Martin (2004) and Bekaert *et al.* (2005).† In the case where there is a single factor a suitable specification is

$$w_t = e_t, \tag{23}$$

where

$$e_t \sim (0, h_t), \tag{24}$$

with conditional volatility h_t, given by the following *GARCH* factor structure (Diebold and Nerlove 1989, Dungey *et al.* 2000)

$$h_t = (1 - \alpha - \beta) + \alpha e_{t-1}^2 + \beta h_{t-1}. \tag{25}$$

The choice of the normalization, $(1 - \alpha - \beta)$, constrains the unconditional volatility to equal unity and is adopted for identification.

Using (10) augmented by (23) to (25) gives the total (conditional) volatility of $y_{2,t}$, the asset return in the crisis period, as

$$\begin{aligned} E_{t-1}\left[y_{2,t}^2\right] &= E_{t-1}\left[\left(\lambda_2 w_t + \delta_2 u_{2,t} + \gamma u_{1,t}\right)^2\right] \\ &= \lambda_2^2 h_t + \delta_2^2 + \gamma^2, \end{aligned}$$

where the assumption of independent factors in (5) and (6) is utilized. The conditional covariance between $y_{1,t}$ and $y_{2,t}$, during the crisis period for example, is

$$\begin{aligned} &E_{t-1}\left[y_{1,t} y_{2,t}\right] \\ &= E_{t-1}\left[\left(\lambda_1 w_t + \delta_1 u_{1,t}\right)\left(\lambda_2 w_t + \delta_2 u_{2,t} + \gamma u_{1,t}\right)\right] \\ &= \lambda_1 \lambda_2 h_t + \gamma \delta_1. \end{aligned}$$

Both the conditional variance and covariance during the crisis period are affected by the presence of contagion ($\gamma \neq 0$). In particular, contagion has the effect of causing a structural shift during the crisis period in the conditional covariance by $\gamma\delta_1$ and the conditional variance by γ^2.

An important advantage of adopting a *GARCH* factor model of asset returns is that it provides a parsimonious multivariate *GARCH* model. This model, when combined with a model of contagion, can capture changes in the variance and covariance structures of asset returns during financial crises.‡ The parsimony of the factor *GARCH* model specification contrasts with multivariate *GARCH* models based on the *BEKK* specification (Engle and Kroner 1995) which require a large number of parameters for even moderate size models.§

4. Correlation and covariance analysis

Forbes and Rigobon (2002) define contagion as the increase in correlation between two variables during a crisis period. In performing their test, the correlation between the two asset returns during the crisis period is adjusted to overcome the problem that correlations are a positive function of volatility. As crisis periods are typically characterized by an increase in volatility, a test based on the (conditional) correlation is biased upwards resulting in evidence of spurious contagion (Boyer *et al.* 1999, Loretan and English 2000, Forbes and Rigobon 2002, Corsetti *et al.* 2003).¶

4.1. Bivariate testing

To demonstrate the Forbes and Rigobon (2002) approach, consider testing for contagion from country 1 to country 2 where the return volatilities are $\sigma_{x,i}^2$ and $\sigma_{y,i}^2$ in the non-crisis and crisis periods respectively. The correlation between the two asset returns is ρ_y during the crisis period (high volatility period) and ρ_x in the non-crisis (low volatility period).‖ If there is an increase in the volatility of the asset return of country 1, $\sigma_{y,1}^2 > \sigma_{x,1}^2$, without there being any change to the fundamental relationship between the asset returns in the two markets, then $\rho_y > \rho_x$ gives the false appearance of contagion. To adjust for this bias, Forbes and Rigobon show that the adjusted (unconditional) correlation is given by (see also Boyer *et al.* 1999, Loretan and English 2000, Corsetti *et al.* 2001, 2003)§§

$$\nu_y = \frac{\rho_y}{\sqrt{1 + [(\sigma_{y,1}^2 - \sigma_{x,1}^2)/\sigma_{x,1}^2]\left(1 - \rho_y^2\right)}}. \tag{26}$$

This is the unconditional correlation (ν_y) which is the conditional correlation (ρ_y) scaled by a nonlinear function of the percentage change in volatility in the asset return of the source country $((\sigma_{y,1}^2 - \sigma_{x,1}^2)/\sigma_{x,1}^2)$, country 1 in this case, over the high and low volatility periods. If there is no fundamental change in the relationship between the two asset markets then $\nu_y = \rho_x$.

To test that there is a significant increase in correlation in the crisis period, the null hypothesis is for no contagion,

$$H_0 : \nu_y = \rho_x, \tag{27}$$

against the alternative hypothesis of

$$H_1 : \nu_y > \rho_x. \tag{28}$$

†See also Chernov *et al.* (2003) for a recent investigation of the dynamics of asset markets.

‡Further extensions to allow for asymmetric shocks are by Dungey *et al.* (2003b) and asymmetric volatility by Bekaert *et al.* (2005).

§Problems in estimating multivariate *GARCH* models are noted by Malliaroupulos (1997), although research on this problem proceeds apace.

¶Butler and Joaquin (2002) conduct the same test across bull and bear markets, although they do not specifically use the terminology of contagion.

‖Forbes and Rigobon (2002) in their empirical application compare the crisis period correlation with the correlation calculated over the total sample period (low volatility period). That is, x is replaced by $z = (x; y)$. This alternative formulation is also discussed below.

§§Other approaches using correlation analysis are Karolyi and Stulz (1996) and Longin and Solnik (1995).

A *t*-statistic for testing this hypothesis is given by

$$FR_1 = \frac{\hat{\nu}_y - \hat{\rho}_x}{\sqrt{(1/T_y) + (1/T_x)}}, \tag{29}$$

where the ˆ signifies the sample estimator, and T_y and T_x are the respective sample sizes of the high volatility and low volatility periods. The standard error in (29) derives from assuming that the two samples are drawn from independent normal distributions. That is,

$$\begin{aligned} \mathrm{Var}(\hat{\nu}_y - \hat{\rho}_x) &= \mathrm{Var}(\hat{\nu}_y) + \mathrm{Var}(\hat{\rho}_x) - 2\,\mathrm{Cov}(\hat{\nu}_y, \hat{\rho}_x) \\ &= \mathrm{Var}(\hat{\nu}_y) + \mathrm{Var}(\hat{\rho}_x) \\ &\simeq \frac{1}{T_y} + \frac{1}{T_x}, \end{aligned} \tag{30}$$

where the second step follows from the independence assumption, and the last step follows from the assumption of normality and the use of an asymptotic approximation (Kendall and Stuart 1973, p. 307). To improve the finite sample properties of the test statistic, Forbes and Rigobon (2002) suggest using the Fisher transformation†

$$FR_2 = \frac{1/2 \ln\left((1+\hat{\nu}_y)/(1-\hat{\nu}_y)\right) - 1/2 \ln\left((1+\hat{\rho}_x)/(1-\hat{\rho}_x)\right)}{\sqrt{(1/T_y - 3) + (1/T_x - 3)}}. \tag{31}$$

In the adjusted correlation test adopted by Forbes and Rigobon (2002) in their empirical work, the non-crisis period is defined as the total sample period. For this case, the test statistic in equation (29) becomes

$$FR_3 = \frac{\hat{\nu}'_y - \hat{\rho}_z}{\sqrt{(1/T_y) + (1/T_z)}}, \tag{32}$$

where x is replaced by z and

$$\hat{\nu}'_y = \frac{\rho_y}{\sqrt{1 + [(\sigma^2_{y,1} - \sigma^2_{z,1})/\sigma^2_{z,1}](1 - \rho^2_y)}}, \tag{33}$$

which is (26) with $\sigma^2_{x,1}$ replaced by $\sigma^2_{z,1}$. From (31), the Fisher adjusted version of the test statistic is

$$FR_4 = \frac{1/2 \ln\left((1+\hat{\nu}_y)/(1-\hat{\nu}_y)\right) - 1/2, ln((1+\hat{\rho}_z)/(1-\hat{\rho}_z))}{\sqrt{(1/T_y - 3) + (1/T_z - 3)}}. \tag{34}$$

Underlying (32) and (34) is the assumption that the variances of $\hat{\nu}'_y$ and $\hat{\rho}_z$ are independent. Clearly this cannot be correct in the case of overlapping data. One implication of this result is that the standard error in (30) is too large as it neglects the (negative) covariance term arising from the use of overlapping data. This biases the *t*-statistic to zero resulting in a failure to reject the null of contagion.

4.2. Alternative formulation

In implementing the correlation test in (29) or (31), equation (26) shows that the conditional correlation needs to be scaled initially by a nonlinear function of the change in volatility in the asset return of the source country, country 1 in this case, over the pertinent sample periods. Another way to implement the Forbes and Rigobon test of contagion is to scale the asset returns and perform the contagion test within a regression framework.‡ Continuing with the example of testing for contagion from the asset market of country 1 to the asset market of country 2, consider scaling the asset returns during the non-crisis period by their respective standard deviations. First, define the following regression equation during the non-crisis period where the returns are scaled by their respective standard errors

$$\left(\frac{x_{2,t}}{\sigma_{x,2}}\right) = \alpha_0 + \alpha_1\left(\frac{x_{1,t}}{\sigma_{x,1}}\right) + \eta_{x,t}, \tag{35}$$

where $\eta_{x,t}$ is a disturbance term and α_0 and α_1 are regression parameters. The non-crisis slope regression parameter equals the non-crisis correlation coefficient, $\alpha_1 = \rho_x$. Second, for the crisis returns the regression equation is given as follows, where the scaling of asset returns is still by the respective standard deviations from the non-crisis periods,

$$\left(\frac{y_{2,t}}{\sigma_{x,2}}\right) = \beta_0 + \beta_1\left(\frac{y_{1,t}}{\sigma_{x,1}}\right) + \eta_{y,t}, \tag{36}$$

where $\eta_{y,t}$ is a disturbance term and β_0 and β_1 are regression parameters. The crisis regression slope parameter $\beta_1 = \nu_y$, which is the Forbes–Rigobon adjusted correlation coefficient given in (26).

This alternative formulation suggests that another way to implement the Forbes–Rigobon adjusted correlation is to estimate (35) and (36) by ordinary least squares (OLS) and test the equality of the regression slope parameters. This test is equivalent to a Chow test for a structural break of the regression slope. Implementation of the test can be based on the following pooled regression equation over the entire sample

$$\left(\frac{z_{2,t}}{\sigma_{x,2}}\right) = \gamma_0 + \gamma_1 d_t + \gamma_2\left(\frac{z_{1,t}}{\sigma_{x,1}}\right) + \gamma_3\left(\frac{z_{1,t}}{\sigma_{x,1}}\right)d_t + \eta_t, \tag{37}$$

†This tranformation is valid for small values of the correlation coefficients, ρ_x and ν_y. Further refinements are discussed in Kendall and Stuart (1969, p. 391). For the case of independence, $\rho_x = \nu_y = 0$, an exact expression for the variance of the transformed correlation coefficient is available. An illustration of these problems for the Forbes and Rigobon method is given in Dungey and Zhumabekova (2001).

‡Corsetti *et al.* (2001) extend the Forbes and Rigobon framework to a model equivalent to the factor structure given in (10). Their approach requires evaluating quantities given by the ratio of the contribution of idiosyncratic and common factors to volatility, δ^2_i/λ^2_i for example. These quantities can be estimated directly using GMM as discussed in section 3.2.

where

$$z_i = \left(x_{i,1}, x_{i,2}, \ldots, x_{i,T_x}, y_{i,1}, y_{i,2}, \ldots, y_{i,T_y}\right)', \quad i = 1, 2, \tag{38}$$

represents the $\left(T_x + T_y\right) \times 1$ pooled data set by stacking the non-crisis and crisis data and η_t is a disturbance term. The slope dummy, d_t, is defined as

$$d_t = \begin{cases} 1: & t > T_x, \\ 0: & \text{otherwise.} \end{cases} \tag{39}$$

The parameter $\gamma_3 = \beta_1 - \alpha_1$ in (37), captures the effect of contagion. It represents the additional contribution of information on asset returns in country 2 to the non-crisis regression: if there is no change in the relationship the dummy variable provides no new additional information during the crisis period, resulting in $\gamma_3 = 0$. Thus the Forbes and Rigobon contagion test can be implemented by estimating (37) by OLS and performing a one-sided t-test of

$$H_0: \gamma_3 = 0, \tag{40}$$

in (37), which is equivalent to testing

$$H_0: \alpha_1 = \beta_1, \tag{41}$$

in (35) and (36).† Of course, the test statistic to perform the contagion test is invariant to scaling transformations of the regressors, such as the use of $\sigma_{x,1}$ and $\sigma_{x,2}$ to standardize z_t. This suggests that an even more direct way to test for contagion is to implement a standard test of parameter constancy in a regression framework simply based on z_t, the unscaled data.‡

There is one difference between the regression approach to correlation testing for contagion based on (37) and the approach implemented by Forbes and Rigobon, and that is the standard errors used in the test statistics are different in small samples. The latter approach is based on the asymptotic adjustment given in (31) or (34), whilst the former are based, in general, on the usual least squares standard errors or some robust estimator.

4.3. *Multivariate testing*

The regression framework developed above for implementing the Forbes and Rigobon test suggests that a multivariate analogue can be easily constructed as follows. Given that there is no need to scale the data to perform the contagion test, in the case of three asset returns the non-crisis period equations are

$$\begin{aligned} x_{1,t} &= \alpha_{1,2}x_{2,t} + \alpha_{1,3}x_{3,t} + \eta_{x,1,t}, \\ x_{2,t} &= \alpha_{2,1}x_{1,t} + \alpha_{2,3}x_{3,t} + \eta_{x,2,t}, \\ x_{3,t} &= \alpha_{3,1}x_{1,t} + \alpha_{3,2}x_{2,t} + \eta_{x,3,t}, \end{aligned} \tag{42}$$

whilst the crisis equations are specified as

$$\begin{aligned} y_{1,t} &= \beta_{1,2}y_{2,t} + \beta_{1,3}y_{3,t} + \eta_{y,1,t}, \\ y_{2,t} &= \beta_{2,1}y_{1,t} + \beta_{2,3}y_{3,t} + \eta_{y,2,t}, \\ y_{3,t} &= \beta_{3,1}y_{1,t} + \beta_{3,2}y_{2,t} + \eta_{y,3,t}, \end{aligned} \tag{43}$$

where $\eta_{x,i,t}$ and $\eta_{y,i,t}$ are error terms. A joint test of contagion is given by

$$\alpha_{i,j} = \beta_{i,j}, \quad \forall i \neq j, \tag{44}$$

which represents 6 restrictions. A convenient way to implement the multivariate version of the Forbes and Rigobon test is to adopt the strategy of (37) and write the model as a 3 equation system augmented by a set of slope dummy variables to capture the impact of contagion on asset returns

$$\begin{aligned} z_{1,t} &= \alpha_{1,2}z_{2,t} + \alpha_{1,3}z_{3,t} + \gamma_{1,2}z_{2,t}d_t + \gamma_{1,3}z_{3,t}d_t + \eta_{1,t}, \\ z_{2,t} &= \alpha_{2,1}z_{1,t} + \alpha_{2,3}z_{3,t} + \gamma_{2,1}z_{1,t}d_t + \gamma_{2,3}z_{3,t}d_t + \eta_{2,t}, \\ z_{3,t} &= \alpha_{3,1}z_{1,t} + \alpha_{3,2}z_{2,t} + \gamma_{3,1}z_{1,t}d_t + \gamma_{3,2}z_{2,t}d_t + \eta_{3,t}, \end{aligned} \tag{45}$$

where the $z_{i,t}$ pooled asset returns are as defined in (38), $\eta_{i,t}$ are disturbance terms, d_t is the dummy variable defined in (39) and $\gamma_{i,j} = \beta_{i,j} - \alpha_{i,j}$ are the parameters which control the strength of contagion.

The multivariate contagion test is based on testing the null hypothesis

$$H_0: \gamma_{i,j} = 0, \quad \forall i \neq j. \tag{46}$$

Implementation of the test can be performed by using standard multivariate test statistics, including likelihood ratio, Wald and Lagrange multiplier statistics.

Rigobon (2003b) suggests an alternative multivariate test of contagion. This test is referred to as the determinant of the change in the covariance matrix (DCC) as it is based on comparing the covariance matrices across two samples (non-crisis and crisis) and taking the determinant to express the statistic as a scalar. The DCC statistic is formally defined as

$$\text{DCC} = \frac{\left|\hat{\Omega}_y - \hat{\Omega}_x\right|}{\hat{\sigma}_{\text{DCC}}}, \tag{47}$$

where $\hat{\Omega}_y$ and $\hat{\Omega}_x$ are the estimated covariance matrices of asset returns in the crisis and non-crisis periods

†Interestingly, Caporale *et al.* (2002) conduct a test of contagion based on a slope dummy, but do not identify the connection of the test with the Forbes and Rigobon (2002) correlation approach.

‡To implement the form of the Forbes and Rigobon (2002) version of the correlation test within the regression framework in (37), the pre-crisis data is now replaced by the total sample data. That is, the low volatility period is defined as the total sample period and not the pre-crisis period. This requires redefining the pertinent variables as $z = (x, y, y)$ and the slope dummy as $d = \left(0_{T_x}, 0_{T_y}, 1_{T_y}\right)$, and scaling the variables using the total sample period.

respectively, and $\hat{\sigma}_{\mathrm{DCC}}$ is an estimate of the pertinent standard error of the statistic. Under the null hypothesis there is no change in the covariance structure of asset returns across sample periods, resulting in a value of $\mathrm{DCC}=0$. If contagion increases volatility during the crisis period, then $\mathrm{DCC}>0$, resulting in a rejection of the null hypothesis of no contagion.

The DCC test represents a test of parameter stability and thus provides an alternative test to a Chow test. However, given the relationship between Chow and contagion tests discussed above, this implies that potentially the DCC test is also a test of contagion. To highlight this point, consider the following bivariate factor model based on the first two equations in (2) and (10). The non-crisis and crisis covariance matrices are respectively

$$\Omega_x = \begin{bmatrix} \lambda_1^2+\delta_1^2 & \lambda_1\lambda_2 \\ \lambda_1\lambda_2 & \lambda_2^2+\delta_2^2 \end{bmatrix},$$

$$\Omega_y = \begin{bmatrix} \lambda_1^2+\delta_1^2 & \lambda_1\lambda_2+\gamma\delta_1 \\ \lambda_1\lambda_2+\gamma\delta_1 & \lambda_2^2+\delta_2^2+\gamma^2 \end{bmatrix}.$$

The numerator of the DCC statistic in this case is

$$\left|\hat{\Omega}_y-\hat{\Omega}_x\right| = \begin{vmatrix} 0 & \hat{\gamma}\hat{\delta}_1 \\ \hat{\gamma}\hat{\delta}_1 & \hat{\gamma}^2 \end{vmatrix} = -\hat{\gamma}^2\hat{\delta}_1^2,$$

where the ^ signifies a parameter estimator. Under the null hypothesis $\mathrm{DCC}=0$, which is achieved when $\gamma=0$, a result that is equivalent to the tests of contagion already discussed.

In implementing the DCC test, the covariance matrices employed tend to be conditional covariance matrices if dynamics arising from lagged variables and other exogenous variables are controlled for. One approach is to estimate a VAR for the total period, T_x+T_y, and base the covariances on the VAR residuals. This is the approach adopted in the empirical application of Rigobon (2003b). The advantage of working with VAR residuals, as compared to structural residuals, is that the VAR represents an unconstrained reduced form, thereby circumventing problems of simultaneity bias. Endogeneity issues are now discussed.

4.4. Endogeneity issues

The potential simultaneity biases arising from the presence of endogenous variables are more evident when the Forbes and Rigobon test is cast in a linear regression framework. Forbes and Rigobon perform the correlation test on pairs of countries under the assumption that contagion spreads from one country to another with the source country being exogenous. The test can then be performed in the reverse direction with the implicit assumption of exogeneity on the two asset returns reversed. Performing the two tests in this way is inappropriate as it clearly ignores the simultaneity bias problem.†

Forbes and Rigobon (2002) show using a Monte Carlo analysis that the size of the simultaneity bias is unlikely to be severe if the size of the correlations between asset returns are relatively small. Interestingly, Rigobon (2003b) notes that the volatility adjustment in performing the test in (26) is incorrect in the presence of simultaneity bias. However, as noted above, the Forbes and Rigobon adjustment acts as a scaling parameter which has no affect on the properties of the test statistic in a linear regression framework. The problem of simultaneity bias is the same whether the endogenous explanatory variables are scaled or not.

To perform the Forbes and Rigobon contagion test while correcting for simultaneity bias, equations (42) and (43) need to be estimated initially using a simultaneous equation estimator and the tests of contagion based on the simultaneous equation estimates of $\gamma_{i,j}$ in (45). To demonstrate some of the issues, the bivariate model is expanded to allow for structural breaks in the idiosyncratic loadings. The bivariate versions of the model without intercepts during the non-crisis and crisis periods are respectively

$$\begin{aligned} x_{1,t} &= \alpha_1 x_{2,t}+\eta_{x,1,t}, \\ x_{2,t} &= \alpha_2 x_{1,t}+\eta_{x,2,t}, \end{aligned} \tag{48}$$

where $\eta_{x,i,t}$ are independent and identically distributed (*iid*) with zero means and variances $E\left[\eta_{x,i}^2\right]=\omega_{x,i}^2$, and

$$\begin{aligned} y_{1,t} &= \beta_1 y_{2,t}+\eta_{y,1,t}, \\ y_{2,t} &= \beta_2 y_{1,t}+\eta_{y,2,t}, \end{aligned} \tag{49}$$

where $\eta_{y,i,t}$ are *iid* with zero means and variances $E\left[\eta_{y,i}^2\right]=\omega_{y,i}^2$. The respective reduced forms are

$$\begin{aligned} x_{1,t} &= \frac{1}{1-\alpha_1\alpha_2}\left(\eta_{x,1,t}+\alpha_1\eta_{x,2,t}\right), \\ x_{2,t} &= \frac{1}{1-\alpha_1\alpha_2}\left(\eta_{x,2,t}+\alpha_2\eta_{x,1,t}\right), \end{aligned} \tag{50}$$

for the non-crisis period and

$$\begin{aligned} y_{1,t} &= \frac{1}{1-\beta_1\beta_2}\left(\eta_{y,1,t}+\beta_1\eta_{y,2,t}\right), \\ y_{2,t} &= \frac{1}{1-\beta_1\beta_2}\left(\eta_{y,2,t}+\beta_2\eta_{y,1,t}\right), \end{aligned} \tag{51}$$

for the crisis period. For the two sub-periods the variance–covariance matrices are respectively

$$\Omega_x = \frac{1}{(1-\alpha_1\alpha_2)^2}\begin{bmatrix} \omega_{x,1}^2+\alpha_1^2\omega_{x,2}^2 & \alpha_1^2\omega_{x,2}^2 \\ \alpha_1\omega_{x,2}^2 & \omega_{x,2}^2+\alpha_2^2\omega_{x,1}^2 \end{bmatrix} \tag{52}$$

†Forbes and Rigobon recognize this problem and do not test for contagion in both directions, being very clear about their exogeneity assumptions.

$$\Omega_y = \frac{1}{(1-\beta_1\beta_2)^2}\begin{bmatrix} \omega_{y,1}^2 + \beta_1^2\omega_{y,2}^2 & \beta_1\omega_{y,2}^2 \\ \beta_1\omega_{y,2}^2 & \omega_{y,2}^2 + \beta_2^2\omega_{y,1}^2 \end{bmatrix}. \quad (53)$$

The model at present is underidentified as there is a total of just 6 unique moments across the two samples, to identify the 8 unknown parameters

$$\{\alpha_1, \alpha_2, \beta_1, \beta_2, \omega_{x,1}^2, \omega_{x,2}^2, \omega_{y,1}^2, \omega_{y,2}^2\}.$$

In a study of the relationship between Mexican and Argentinian bonds, Rigobon (2003a) identifies the model by setting $\alpha_1 = \beta_1$ and $\alpha_2 = \beta_2$. However, from (41), this implies that there is no contagion, just a structural break in the idiosyncratic variances. An alternative approach to identification, which is more informative in the context of testing for contagion, is not to allow for a structural break and set $\omega_{x,1}^2 = \omega_{y,1}^2$ and $\omega_{x,2}^2 = \omega_{y,2}^2$. Now there are 6 equations to identify the 6 unknowns. A test of contagion is given by a test of the over-identifying restrictions under the null hypothesis of no contagion. The observational equivalence between the two identification strategies has already been noted above in the discussion of the factor model. However, if the idiosyncratic variances are changing over the sample, the contagion test is undersized (Toyoda and Ohtani 1986). Another alternative solution is to expand the number of asset markets investigated. For example, increasing the number of assets to $N = 3$ results in a just identified model as there are 12 unknown parameters,

$$\{\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3, \omega_{x,1}^2, \omega_{x,2}^2, \omega_{x,3}^2, \omega_{y,1}^2, \omega_{y,2}^2, \omega_{y,3}^2\},$$

and 12 moments, as there are 6 unique moments from each of the variance–covariance matrices from the two sub-periods.

Rigobon (2002) also suggests using instrumental variables to obtain consistent parameter estimates with the instruments defined as

$$s_i = \left(-x_{i,1}, -x_{i,2}, \ldots, -x_{i,T_x} \quad y_{i,1}, y_{i,2}, \ldots, y_{i,T_y}\right)', \quad i = 1, 2.$$

This choice of instruments is an extension of the early suggestions of Wald (1940) and Durbin (1954). For example, Wald defined the instrument set as a dummy variable with a 1 signifying observations above the median and a -1 for observations below the median. In the case of contagion and modelling financial crises, observations above (below) the median can be expected to correspond to crisis (non-crisis) observations. This suggests that the Rigobon instrument is likely to be more efficient than the instrument chosen by Wald as it uses more information. Rigobon then proceeds to estimate pooled equations as in (45), but with $\gamma_{i,j} = 0$. But this is not a test of contagion as $\alpha_i = \beta_i$ is imposed and not tested. Not surprisingly, the instrumental variables (IV) estimator of the structural parameters in this case, is equivalent to the matching moment estimator using (52) and (53), subject to the restrictions $\alpha_1 = \beta_1$ and $\alpha_2 = \beta_2$.

4.5. Relationship with other models

Interpreting the Forbes and Rigobon contagion test as a Chow test provides an important link connecting this approach with the contagion modelling framework of Dungey *et al.* (2002, 2005b) discussed in the previous section. To highlight this link, let the dynamics of the processes be represented by the first two expressions of the contagion model in (10)

$$y_{1,t} = \lambda_1 w_t + \delta_1 u_{1,t}, \quad (54)$$

$$y_{2,t} = \lambda_2 w_t + \delta_2 u_{2,t} + \gamma u_{1,t}, \quad (55)$$

where, as before, contagion from the asset market in country 1 to country 2 is controlled by the parameter γ. Combining these expressions to substitute out $u_{1,t}$ from the equation for $y_{2,t}$ gives

$$y_{2,t} = \left(\frac{\lambda_2\delta_1 - \lambda_1\gamma}{\delta_1}\right) w_t + \frac{\gamma}{\delta_1} y_{1,t} + \delta_2 u_{2,t}. \quad (56)$$

The corresponding asset equation in the non-crisis period is given by setting $\gamma = 0$ and changing $y_{i,t}$ to $x_{i,t}$,

$$x_{2,t} = \left(\frac{\lambda_2\delta_1 - \lambda_1\gamma}{\delta_1}\right) w_t + \delta_2 u_{2,t}. \quad (57)$$

Stacking equations (57) and (56) yields an equation of the same form as (37) provided that the common factor is taken as $w_t = z_{1,t}$, the stacked vector of asset returns in country 1 across non-crisis and crisis periods. In this scenario the Forbes and Rigobon and Dungey *et al.* (DFGM) approaches are equivalent with the test of contagion still being based on $\gamma = 0$. This amounts to testing the additional explanatory power of the asset returns in country 1 to explain movements in the asset returns in country 2 over and above the factors that govern movements in asset markets during non-crisis periods.

In practice, Forbes and Rigobon (2002) identify the common factor w_t using a number of observed variables including US interest rates. These variables are initially extracted from the asset returns data by regressing the returns on the chosen set of common factors and using the residuals from these regressions in the contagion tests given in (26) to (31). In conducting the contagion tests, the analysis is performed in pairs with the source country changing depending on the hypothesis being tested. This testing strategy is highlighted in (56) and (57) where the source country is country 1.

Testing for contagion, based on the dummy variable version of the Forbes and Rigobon contagion test in equation (37), also introduces the links to a range of other tests for contagion. For example, the approach of Favero and Giavazzi (2002) consists of defining the dummy variable in (39) as

$$d_{i,t} = \begin{cases} 1: & |u_{i,t}| > 3\delta_i, \\ 0: & \text{otherwise}, \end{cases} \quad (58)$$

where δ_i is computed as the standard deviation of the residuals in a VAR(p) associated with the variable

$y_{i,t}$.† A structural model is then specified where each return is expressed as a function of all other returns, own lagged returns and the full set of dummy variables. The system of equations is estimated by full information maximum likelihood (FIML) and the contagion test is based on a joint test of the parameters on the dummy variables of the other returns. The test will identify contagion if extreme returns in the dependent variable are matched with extreme returns in the other variables. The dummy variables define the period of the crisis. This contrasts with the approach of Forbes and Rigobon and DFGM, where the crisis period is determined *a priori*. One implication of the Favero and Giavazzi test is that the results can potentially be driven by a small number of observations thereby making the test rather fragile. A further implication of this approach concerns the use of lag variables to identify the simultaneous equations model. In the case where it is asset returns that are being modelled, the autocorrelation structure of asset returns is expected to be low.‡ This results in a weak instrument problem where the bias of a simultaneous estimator can exceed the bias of the OLS estimator which, in turn, can yield spurious results (Nelson and Startz 1990, Stock *et al.* 2002).

Eichengreen *et al.* (1995, 1996) choose dummy variables for both $y_{1,t}$ and $y_{2,t}$ respectively as

$$d_{1,t} = \begin{cases} 1: & y_{1,t} > f(EMP_{1,t}), \\ 0: & \text{otherwise}, \end{cases}$$
$$d_{2,t} = \begin{cases} 1: & y_{2,t} > f(EMP_{2,t}), \\ 0: & \text{otherwise}, \end{cases} \tag{59}$$

where $\text{EMP}_{i,t}$ is the exchange market pressure index.§ As a result of the binary dependent variable the model is estimated as a probit model. Bae *et al.* (2003) extend this model to provide for polychotomous variables, where the dummy variables, $d_{i,t}$, are defined as exceedances

$$d_{1,t} = \begin{cases} 1: & |y_{1,t}| > \text{THRESH}, \\ 0: & \text{otherwise}, \end{cases}$$
$$d_{2,t} = \begin{cases} 1: & |y_{2,t}| > \text{THRESH}, \\ 0: & \text{otherwise}. \end{cases} \tag{61}$$

In their application THRESH is chosen to identify the 5% of extreme observations in the sample. A co-exceedance occurs when $d_{1,t} = d_{2,t} = 1$. The number of exceedances and co-exceedances at time t yields a polychotomous variable which is then used in a multinominal logit model to test for contagion.¶

An important part of the Eichengreen *et al.* (1995, 1996) approach is that it requires choosing the threshold value of the EMP index for classifying asset returns into crisis and non-crisis periods. As with the threshold values adopted by Favero and Giavazzi (2002) and Bae *et al.* (2003), the empirical results are contingent on the choice of the threshold value. In each of these approaches, this choice is based on sample estimates of the data, resulting in potentially non-unique classifications of the data for different sample periods.‖

The construction of binary dummies in (58) to (61) in general amounts to a loss of sample information resulting in inefficient parameter estimates and a loss of power in testing for contagion. A more direct approach which does not result in any loss of sample information is to estimate (56) by least squares and perform a test of contagion by undertaking a t-test of γ. In fact, the probit model delivers consistent estimates of the same unknown parameters given in (56), but these estimates suffer a loss of efficiency as a result of the loss of sample information in constructing the dummy variables.§§

5. Empirical application: equity markets in 1997–1998

To illustrate the application of the alternative empirical methodologies discussed above, this section explores the turmoil in equity markets resulting from the speculative attack on the Hong Kong currency in October 1997.¶¶ This attack was successfully defended by the Hong Kong Monetary Authority, but resulted in a substantial decline in Hong Kong equity markets. A number of Asian

†In a related approach, Pesaran and Pick (2003) also identify outliers by constructing dummy variables which are used in a structural model to test for contagion. One important difference is that Pesaran and Pick do not define the dummy variables for each outlier, but combine the outliers associated with each dummy variable.

‡This is less of a problem in the application considered by Favero and Giavazzi (2002) who used interest rates which have strong autocorrelation structures.

§The threshold indicator $\text{EMP}_{i,t}$ represents the Exchange Market Pressure Index corresponding to the ith asset return at time t, which is computed as a linear combination of the change in exchange rates, interest differentials and changes in levels of reserve assets for country i with respect to some numeraire country, 0,

$$\text{EMP}_{i,t} = a\Delta e_{i,t} + b(r_{i,t} - r_{0,t}) + c(\Delta R_{i,t} - \Delta R_{0,t}), \tag{60}$$

where e_i is the log of the bilateral exchange rate, r_i is the short-term interest rate and R_i is the stock of reserve assets. The weights, a, b and c, are given by the inverse of the standard deviation of the individual component series over the sample period. Kaminsky and Reinhart (2000) adopt a different weighting scheme whereby the weight on interest rates is zero.

¶In the application of Bae *et al.* (2003) the cases of negative and positive returns are considered separately. They also combined all exceedances into a single category. However, by separating the exceedances of each variable it is possible to test for contagion from the host country to the remaining countries separately, see Dungey *et al.* (2005a). This is done in the application in section 5.

‖Both Eichengreen *et al.* and Kaminsky and Reinhart (2000) use some matching of their crisis index constructed using these thresholds to market events to validate the threshold choice.

§§The dummy variable framework can be extended further by allowing for asymmetric shocks (Kaminsky and Schmukler 1999, Baig and Goldfajn 2000, Ellis and Lewis 2000, Butler and Joaquin 2002, Dungey *et al.* 2003b).

¶¶This application is based on Dungey *et al.* (2005a).

markets were also affected. This application considers the potential contagion from this crisis to the equity markets of Korea and Malaysia, with the US equity markets used as a control for common shocks, as per Forbes and Rigobon (2002).

The non-crisis period covers from 1 January 1997 to 17 October 1997. The Hong Kong equity markets declined rapidly beginning 20–23 October 1997. The Hang Seng Index fell by almost a quarter and was associated with large falls in other international markets including Japan, the US and local Asian indices. The crisis period here covers from 20 October 1997 to 31 August 1998, a period often associated with the end of the Asian financial crisis, marked by the repegging of the Malaysian ringgitt.

The example presented here is not intended as a definitive analysis of this crisis, but serves rather as an example of the application of the contagion testing procedures outlined in the first part of the paper. Further analysis of this particular data set and crisis are presented in Dungey *et al.* (2005a) and other analyses of the Asian crisis episode include Forbes and Rigobon (2002), Bae *et al.* (2003) and Dungey *et al.* (2003b).

5.1. Stylized facts

Table 1 contains some descriptive statistics as well as variance–covariances of equity returns during the non-crisis and crisis sample periods for the three countries. The increase in volatility experienced during the crisis period is evident by the large increase in the variances in each country. In the case of Hong Kong the variance in equities rises over threefold, while for both Korea and Malaysia there is more than a fivefold increase. All countries experience a fall in their average returns during the crisis period. In addition, for each country the extreme minimum and maximum daily return occurs during the crisis period.

5.2. Implementation issues

There are a number of practical issues in implementing the contagion tests outlined in the previous sections. These include identifying the crisis period from the non-crisis period, the use of proxy variables to identify common factors, choice of frequency of data and the treatment of missing observations and time zones. Each of these issues is dealt with in more detail in the companion paper Dungey *et al.* (2005a), but are briefly outlined in what follows.

There are two broad approaches to identifying the timing of crises. The first approach is based on ex post observation of events in the existing literature as in Forbes and Rigobon (2002) (the FR test) and Dungey *et al.* (2005b) (the DFGM test). The second approach is based on the identification of some threshold value, such as in Favero and Giavazzi (2002) (the FG test), Bae *et al.* (2003) (the BKS test) and Eichengreen *et al.* (1996).

The choice of proxy variables for the common factors is often related to the choice of data frequency. One group of researchers recognizes contagion in its effects on relatively low frequency data where appropriate macroeconomic controls can be taken into account, for example Eichengreen *et al.* (1995, 1996). Then there are those who would presumably prefer to test at higher frequency, but are constrained by the availability of control data, such as Glick and Rose (1999) who consider trade flows. And finally the majority of studies consider contagion in relatively high frequency data, at either daily or weekly frequency, where contagion is viewed as a relatively short-lived phenomenon. This is the case with all of the correlation analysis studies, most of the extreme value studies, threshold models and the latent factor models. Some studies also utilize observed high frequency data as common variable controls, such as in Forbes and Rigobon (2002) who use US interest rates. This is the approach adopted in the empirical application whereby a VAR containing one lag and US returns is estimated, with the residuals representing the filtered returns. This pre-filtering of the data is used in the calculations of the DFGM, FR and BKS tests, but not the FG test so as to be commensurate with their methodology.

To allow for differences in the time zones between the US and the three Asian equity markets, the US interest rates are dated at time $t-1$. In general, time zone alignment problems arise because markets may be open on nominally the same date, but there may be no actual trading time overlap. Kaminsky and Reinhart (2003)

Table 1. Descriptive statistics and variance–covariances of daily percentage equity returns for selected sample periods: non-crisis period (1 January 1997 to 17 October 1997), crisis period (20 October 1997 to 31 August 1998).

	Non-crisis period			Crisis period		
	Hong Kong	Korea	Malaysia	Hong Kong	Korea	Malaysia
Descriptive statistics						
Mean	0.004	−0.056	−0.209	−0.300	−0.300	−0.468
Max	6.883	4.019	1.666	17.247	10.024	20.817
Min	−5.150	−4.306	−5.817	−14.735	−11.601	−11.744
Covariance matrix						
Hong Kong	2.238			10.794		
Korea	0.260	2.045		1.611	13.114	
Malaysia	0.631	0.063	2.782	4.716	3.348	10.291

find significant time zone effects in equity markets. One approach to this problem is to control for differences in time zones by using moving averages of returns (Forbes and Rigobon 2002, Ellis and Lewis 2000). However, this may mask movements in asset prices and hence introduce biases into the tests of contagion. Bae *et al.* (2003) choose different lags depending on the time zone under investigation, which works because two distinct time zones are involved. Dungey *et al.* (2003a) suggest using simulation methods by treating time zone problems as a missing observation issue.

Finally, missing observations cause problems in tracking volatility across markets in a single period, and are usually dealt with by either replacing the missing observation with the previous market observation or removing that data point from the investigation. In practice, most researchers seem to use a strategy of excluding days corresponding to missing observations, which is the approach adopted below.

5.3. Contagion testing

To gain some insight into the relative size of contagion amongst equity markets during the crisis, table 2 provides the DFGM factor decompositions of the variances and the covariances given in table 1. As the model is just identified these decompositions provide a breakdown of these moments in terms of the underlying factors, including contagion.

The variance decompositions in table 2 show that asset return volatility during the crisis is dominated by contagion with much smaller contributions from the world and idiosyncratic factors. The dominant contagion channels are from Hong Kong to both Korea (7.972) and Malaysia (5.972), which are over 50% of the total volatility of the returns in these two countries (13.114 and 10.291 respectively). There are also important reverse contagion channels from Korea and Malaysia to Hong Kong (3.705 and 4.858), and from Malaysia to Korea (3.181).

The covariance decompositions in table 2 reveal that contagion from Hong Kong had positive impacts on the covariances between all asset returns. In contrast, contagion from Korea and Malaysia tended to have a negative impact on several of the covariances.

The volatility decompositions discussed above provide a description of the relative magnitude of contagion linking the three equity markets. To examine the strength of these linkages more formally, table 3 presents the results of 7 contagion tests. The first column gives the country from which contagion is assumed to emanate (labelled Host). The second column gives the recipient country. The remaining 7 columns give the results of the contagion tests based on the DFGM test, the FR test with overlapping data (FR-0) and with non-overlapping data (FR-N), the multivariate version of the FR test (FRM), the FG test with an endogeneity correction (FG-E) and a non-endogeneity corrected version (FG-N), and the BKS test. The row headed 'Both' in each panel of the table gives the results of a joint test of contagion from the host country to the two recipient countries. The last panel of the table gives the results of the joint test of no contagion amongst all three countries.

The results in table 3 show that the Forbes and Rigobon test (FR-O) finds no evidence of contagion in

Table 2. Unconditional volatility decompositions of Asian equity markets during the crisis period, expressed in squared returns: based on equations (19) and (20).

	Country		
	Variance decomposition		
Components	Hong Kong	Korea	Malaysia
World factor	0.057	1.755	0.017
Idiosyncratic factor	2.174	0.279	2.760
Contagion from:			
Hong Kong	–	7.972	5.792
Korea	3.705	–	1.723
Malaysia	4.858	3.181	–
Sub-total	8.563	11.153	7.515
Total	10.794	13.114	10.291
	Covariance decomposition		
	Hong Kong/Korea	Hong Kong/Malaysia	Korea/Malaysia
World factor	0.317	0.032	0.175
Idiosyncratic factor	0.000	0.000	0.000
Contagion from:			
Hong Kong	4.163	3.549	6.795
Korea	1.017	−2.526	−0.693
Malaysia	−3.886	3.662	−2.929
Sub-total	1.294	4.685	3.173
Total	1.611	4.716	3.348

Table 3. Contagion tests of Asian equity markets Hong Kong (HK), Korea (K) and Malaysia (M): p values in parentheses. A * denotes statistically significant at the 5% level.

Host	Recipient	DFGM[a]	FR-O[b]	FR-N[b]	FRM[c]	FG-E[d]	FG-N[d]	BKS[e]
HK to:	K	158.17*	−0.295	−1.002	1.175	117.582*	7.589	2.210
		(0.000)	(0.616)	(0.842)	(0.278)	(0.000)	(0.180)	(0.137)
	M	1.574	−0.507	−0.263	1.162	137.669*	8.881	6.015*
		(0.210)	(0.694)	(0.604)	(0.281)	(0.000)	(0.114)	(0.014)
	Both	182.063*	–		1.968	217.451*	17.850	10.019*
		(0.000)			(0.374)	(0.000)	(0.058)	(0.002)
K to:	HK	45.651*	−0.315	−1.062	1.518	304.902*	11.077	2.146
		(0.000)	(0.624)	(0.856)	(0.218)	(0.000)	(0.086)	(0.143)
	M	12.085*	−0.256	0.209	1.031	356.649*	17.549	2.369
		(0.001)	(0.601)	(0.417)	(0.310)	(0.000)	(0.007)	(0.124)
	Both	439.764*	–		1.872	65.402*	33.911	8.517*
		(0.000)			(0.392)	(0.000)	0.001	(0.004)
M to:	HK	53.578*	−0.348	0.189	6.582*	146.704*	23.251	6.862*
		(0.000)	(0.636)	(0.425)	(0.010)	(0.000)	(0.002)	(0.009)
	K	0.773	−0.105	0.650	4.963*	73.385*	24.636	2.181
		(0.379)	(0.542)	(0.258)	(0.026)	(0.000)	(0.001)	(0.140)
	Both	70.005*	–	–	10.765*	202.745*	51.439	11.145*
		(0.000)			(0.005)	(0.000)	(0.000)	(0.001)
Joint		772.474*	–	–	14.357*	1085.284*	101.973	–
		(0.000)			(0.026)	(0.000)	(0.000)	

[a]Dungey *et al.* test: a Wald test using the GMM parameter estimates of $\gamma_{i,j}$ in (17).
[b]Forbes and Rigobon tests: FR-O is based on overlapping data using (34) and FR-N is based on non-overlapping data using (31).
[c]Multivariate Forbes and Rigobon tests: based on a Wald test using the least-squares parameter estimates of $\gamma_{i,j}$ in (45).
[d]Favero and Giavazzi tests: FG-E and FG-N are the IV (endogeneity corrected) and OLS (non-endogeneity corrected) Favero and Giavazzi tests respectively. Tests based on likelihood ratio tests on the parameters of the dummy variables defined in (58), in a trivariate structural system where each return is expressed as a function of the remaining contemporaneous asset returns, own lagged returns and the set of dummy variables.
[e]Bae *et al.* test: based on defining the dummy variables as in (61) and using Wald tests applied to the maximum likelihood estimates of a multinomial logit model.

any of the channels tested. This lack of any rejection of the null hypothesis is consistent with the discussion in section 4 where it was concluded that this is a conservative test as it is biased towards zero as a result of the variance of the test statistic being incorrect when the non-crisis period is defined as the total sample period.

To examine the issue concerning the downward bias in the Forbes and Rigobon test further, the results of the Forbes and Rigobon test (FR-N), where the non-crisis period is based on non-overlapping data, are also presented in table 3. The results show that 4 of the 6 bivariate contagion tests do indeed lead to lower p values. However, at the 5% level, this test still seems to be conservative as it does not identify any significant contagion linkages. Further confirmation of the bias in the Forbes and Rigobon test FR-O, arising from overlapping data, is given by the multivariate version of the Forbes and Rigobon test (FRM). Here the results point to uniformly stronger contagious linkages, that is lower p values, with signifciant evidence of contagion detected from Malaysia to both Hong Kong and Korea.

In complete contrast to the FR test results in table 3, the FG test (FG-E) finds evidence of contagion in all cases.† To control for potential weak instrument problems, the Favero and Giavazzi test is recomputed with no endogeneity correction (FG-N) by simply estimating the pertinent structural model by OLS. The results show a very different story with now just half of the bivariate contagion tests showing significant evidence of contagion at the 5% level. The strong evidence of contagion based on FG-E appear to be spurious and arise from the presence of weak instruments.‡ Comparing the results of the FG-N test and DFGM tests shows that the two methods produce similar qualitative results in 4 of the 6 bivariate cases at the 10% level. The two differences are the test of contagion from Hong Kong to Korea where the DFGM test finds evidence of contagion, and the test of contagion from Malaysia to Korea where the FG-N test finds evidence of contagion. The transmission channel from Hong Kong to Korea identified by the DFGM test is consistent with the strong level of contagion identified in the variance decomposition given in table 2. In addition, the lack of significant evidence of contagion from Malaysia to Korea identified by the DFGM test is also consistent with the moderate level of contagion identified in the variance decomposition in table 2 as well.

†The Favero and Giavazzi test based on the dummy variable in (58) identifies 19 outliers: 1 common outlier, 5 outliers in Hong Kong, 6 in Korea and 7 in Malaysia.
‡Performing the weak instrument test based on the F-test of the regressors in the three reduced form equations yields values of 12.893, 7.618 and 15.369. Using the critical values reported in Stock *et al.* (2002: table 1), shows that the null of a weak instrument is not rejected.

The last test results reported in table 3 are for the Bae *et al.* (BKS) test.† Comparing the bivariate DFGM and BKS results shows that the two testing procedures give opposite results where Hong Kong and Korea are the hosts, but the same results where Malaysia is the host. Part of the explanation underlying these results could be the dating of the crisis period which is determined *a priori* in the case of the DFGM test, whereas for the BKS test is determined endogenously. An additional issue surrounding the BKS test is that it discards information in constructing the dummy dependent and independent variables, which may in turn lead to a loss of efficieny in the parameter estimates.

In general, these results in table 3 provide evidence of the difficulties in obtaining consistent information on the existence of contagion from the different tests. This is not unique to this example, similar outcomes emerge in other applied examples for the 1994 Mexican crisis and the 2001 Argentine crisis provided in Dungey *et al.* (2005a). Some of these problems are shown by Dungey *et al.* (2004) to be due to low power and poor size properties of these various tests of contagion.

6. Conclusions and suggestions for future research

This paper has overviewed a number of important tests for the presence and characteristics of contagion in financial markets adopted in the current literature. Using a framework of a latent factor model similar to that proposed in the finance literature, the different testing methodologies are shown to be related. In essence, each method is shown to be a test on a common parameter regarding the transmission of a shock from one country or market to another.

An important result of this paper is that the main distinguishing feature of alternative empirical models of contagion is the way in which the information is used to identify contagion. Dungey *et al.* (2005b) and Forbes and Rigobon (2002) use the information on all of the shocks in the crisis period to test for contagion. Under certain conditions these two models are the same. Favero and Giavazzi (2002) utilize shift dummies at selected crisis points to represent potentially contagious transmissions. Eichengreen *et al.* (1995, 1996) also use dummy variables to identify contagion, however they transform both the dependent and independent indicators into binary variables, which results in a further reduction of the information used in estimation. Bae *et al.* (2003) provide an extension of the Eichengreen *et al.* approach by allowing for a polychotomous dependent variable, based on the number of co-exceedances in their crisis indicator.

Some of the properties and relationships of the various contagion tests were demonstrated in an empirical application of the Asian crisis of 1997–1998. A number of empirical issues concerning missing observations, time zones, dating of crises and data frequency were also discussed. The results showed that the Forbes and Rigobon contagion test was a conservative test as it failed to find evidence of contagion in any of the linkages tested. The Favero and Giavazzi test was at the other extreme, finding evidence of contagion in all cases investigated. Much of this evidence of linkages was found to be spurious, being the result of weak instruments. Correcting the Favero and Giavazzi test for weak instruments yielded contagion channels similar to the channels identified by the DFGM test. The BKS test results tended to be inconsistent with the results of these last two tests. In general, the empirical results of the tests highlighted the need for investigating the sampling properties of the various tests with an extensive Monte Carlo design that looks at issues such as the dating of crises, the modelling of dynamics, the information effects of filtering. Some of these issues have been tackled in Dungey *et al.* (2004) who use a number of Monte Carlo experiments to demonstrate the size and power properties of many of these tests.

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