

Volatility spillovers and the role of leading financial centres*

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In the late 1980s the increasing integration of international financial markets renewed interest in the factors that explain stock price movements. Understanding financial market volatility behaviour is not only an intellectual challenge but also has important implications for portfolio selection and asset management techniques. The October 1987 crash was followed by a spate of statistical studies aimed at investigating the structure and the evolution over time of stock market interlinkages. The Mexican crisis of 1995 and the Pacific Basin financial turmoil prompted the development of tentative theoretical interpretations of the transmission of stock market jolts in periods of stress, the so-called contagion phenomenon.

Economic theory does not provide simple rules on how stock prices in different countries should interact. Studies by Fama (1981 and 1990), Kaul (1987) and Chen (1991) among many others linked stock market behaviour to macroeconomic fundamentals, but shed little light on high frequency stock price changes and international linkages. It is widely accepted that short term price movements are influenced more by changes in aggregate stock market demand (whatever their origin) than by industry specific factors. Movements in a national stock market can propagate immediately to foreign stock prices through information sharing and free access by domestic and

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foreign investors. They may alternatively – as we shall see below – reflect rational portfolio adjustments to news or irrational herding behaviour.

This paper investigates volatility spillovers between twelve equity markets located in Europe, Asia, Latin America and North America (the US market) from July 1992 to July 1999. The VAR methodology – duly adjusted to different market trading times – is used to examine volatility dependencies across the Asian crisis and to simulate the way local volatility responds to the volatility of another market.

The analysis differs from previous works in several aspects.

i) The scope of the research is large and involves three main geographical areas, namely Asia, Europe and South America. A hierarchical structure is imposed in the analysis, as the US is included in each area under investigation. World analysis is also performed by including the five most important markets (in the three areas) selected on the basis of their capitalisation, the idea being to assess if and how the crises affect stock market volatility linkages, i.e. whether crisis contagion is of a regional or worldwide nature. In this respect our paper is an extension of the “heat wave-meteor shower” literature of Engle, Ito and Lin (1990).

ii) The absolute value of the stock returns was chosen as volatility index in order to minimise distortions due to non normality and heteroskedasticity.¹ Impulse responses and variance decomposition analyses were implemented using VAR residuals filtered using GARCH models, as most impulse response inference techniques postulate a normal i.i.d. distribution of the residuals.

Market linkages are examined using returns expressed in local currency and any effect due to foreign exchange fluctuations is assumed away *a priori*. The rationale for not expressing returns in a common currency – e.g. the US dollar – is to separate stock equity from currency risk (Longin and Solnik 1995). As pointed out by Giannopoulos (1998), the two risks are not additive, and expressing the domestic returns in a common currency would blur the volatility

¹ Taylor (1986) suggests, after an extensive empirical investigation, that stock market volatility is modelled better by absolute values of the returns than by their squared values. Ding and Granger (1996) arrive at analogous conclusions with a PGARCH parameterisation of conditional variance.

interpretation. Each return series would be a combination of equity returns and the dollar price in terms of the local currency.

The paper is organised as follows. Section 1 presents a short description of the Asian crisis and discusses its anomalous international financial transmission. It also provides a survey of the most recent theoretical interpretations of the latter. Section 2 presents a preliminary description of the individual stock return time series over the two sub-samples of interest. Section 3 investigates the characteristics of the VAR models that link the volatility time series. Section 4 exhibits the main empirical findings on volatility transmission in the geographical areas of interest and assesses their economic implications. Section 5 concludes the paper.

1. The Asian crisis and stock market contagion

After a decade of relative calm, the Asian crisis renewed interest in the mechanisms of volatility transmission across international equity markets. In this section the role played by the major financial centres is analysed in a chronological perspective and the contagion hypothesis is set out in accordance with the most recent developments in the literature.

1.1. *The Asian crisis*

Three elements seem to explain the onset of the Asian crisis: appreciation of the real exchange rate due to the upsurge of the dollar, the rise of nominal and real interest rates and the fragility of the local banking and financial systems.

The appreciation of the real exchange rate and the subsequent current account imbalances had strong destabilising deflationary effects. In January 1997 a large Korean *chaebol* went bankrupt for the first time in a decade. In May exchange rate speculation struck currencies believed to be overvalued. Thailand's monetary authorities caved in and the baht was allowed to float on July 2, losing up to 20% of its value. The neighbouring countries could only follow

suit.² The turbulence reached Indonesia in August and Taiwan in October. The latter was also forced to devalue its currency, generating doubts, in a domino-like scenario, about Hong Kong's ability to maintain its currency peg to the US dollar.

Exchange rate tension destabilised Hong Kong's equity market as sharp interest rate increases stemmed liquidity supply.³ By the end of October the Hong Kong stock market had lost a quarter of its value through fears of further interest rate increases and pressures on the exchange rate.

The fragility of the local banking systems, which were unable to cope with the adverse movements of the main financial variables, had an unexpected magnifying effect. Some important institutions were downgraded by the major international rating agencies as their share of non-performing loans rose due to the economic downturn, and others collapsed. Indeed, fear that the crisis would involve some primary Japanese financial institutions was instrumental in transferring instability to the American and Japanese equity markets. The Dow Jones went down by almost 7% on 27th October, and the plunge had strong repercussions on the Latin American markets. European markets fell by 8% the following day. The first wave of the crisis culminated with the collapse of the Korean won at the beginning of November.

The epicentre of the crisis moved back to Japan by the end of the month as new doubts arose about the solvency of some local banks. In December instability spread from South Korea and Indonesia throughout the Pacific rim and to Latin America, where stock markets slumped again. At the end of the month a 5% plunge of the Nikkei triggered a new wave of panic in the region. After a lull at the beginning of 1998 the combined effects of additional mishaps involving Japanese financial institutions and of political instability in Indo-

² The Philippine peso was devalued on 11th July and the Malaysian ringgit on 13th. For an econometric interpretation of these devaluations using the PPP paradigm see Chinn (1999).

³ On October 23 the overnight short term interest rate rose to 300% and the following day the equity market recorded a 10% decline. The information reported here comes from the IMF *World Economic Outlook* (May 1998, December 1998 and May 1999 issues), Corsetti, Pesenti and Roubini (1998) and Roubini's "Chronology of the Asian currency crisis and its global contagion" set out in his home page <http://www.stern.nyu.edu/nroubini>.

nesia, Korea and Malaysia triggered a new bout of financial turbulence and a new decline in stock prices.

In August 1998 the announcement from Russia of a surprise partial repudiation of its public debt brought about a new wave of instability across equity markets following the usual pattern of transmission. Some markets experienced price decreases of over 10%. In January the turmoil moved on to Brazil, which was forced to devalue the real by over 30%. The consequences of the Brazilian crisis on international stock price volatility were, however, less severe. According to the IMF, a possible explanation is that investors had already deleveraged most of their exposure to emerging markets, following the Russian crisis and the LTCM (near) collapse.

The above analysis suggests that the recent crises are not easy to disentangle as no single event acts as the catalyst of turmoil. A pattern of financial turbulence transmission can, however, be tentatively identified.

Shocks are abrupt and large in absolute value. They originate outside the main (US and European) international equity markets and may be preceded by exchange rate turbulence. They are rapidly transmitted across markets, even to countries having no significant economic connections with the country originating them. Interlinkages seem to be due mostly to short term rational and irrational financial behaviour.

The major financial markets play a pivotal role in propagating turbulence. The volatility linkages between several of the equity markets under investigation – and this is possible evidence of contagion – are indirect, as they are transmitted via one or more major international financial centre. This characteristic requires that one such centre (at least) be included in any empirical analysis involving the markets of the emerging countries of interest.

1.2. Efficiency, news and international volatility transmission

Sound economics explains why the returns and the volatility of national stock markets should be interlinked. The respective economies may be related through trade and/or financial flows and news about economic fundamentals in one country may well have implications for its neighbours.

An initial line of research focused on the difficulties of sorting out the information relevant for the domestic market, i.e. filtering the foreign news relevant for the national market. Domestic investors have to infer, at the beginning of each day, how much of the foreign price variation observed is due to global events and is of interest. Consequently, King and Wadhvani (1990) and Lin, Engle and Ito (1994) modelled this issue as a signal extraction problem. Rational investors are assumed to extract the unobserved global factors (i.e. the fraction of variance of foreign returns associated with these factors) from observed price changes with the help of a Kalman filter. The accuracy of this procedure declines in periods of turbulence, which may witness abnormal (excessive) market interlinkages and erratic reactions to foreign news.

As in the case of domestic financial and monetary theory, a (possibly irrational) herding behaviour has been identified in periods of market stress, which is assumed to give rise to contagion in international market prices and returns, i.e. to a situation in which “stock prices in a country may be affected by changes in another country beyond what is conceivable through economic fundamentals” (Lin, Engle and Ito 1994, p. 508).⁴

Masson (1998) distinguishes among three major propagation mechanisms of shocks across markets. The first mechanism may be due to common simultaneous shocks affecting different countries with similar effects, the second mechanism to the fact that a shock in one country may affect the economic fundamentals of another. The last mechanism, consisting in pure contagion or herding behaviour, is due to a shift in market sentiment or changes in the interpretation of existing information unrelated to the economic fundamentals. According to Masson, pure contagion is associated with self-fulfilling expectations and multiple equilibria.

Herding behaviour interpretations (e.g. Calvo and Mendoza 1996) posit that it is costly to acquire information, especially in the emerging economies. Investors tend to follow the market rather than take the time and undertake the expense to analyse the behaviour of market fundamentals. Fads and rumours may then explain excessive volatility and speculative attacks. The short-terminism of financial

⁴ They are the first to point out that, in a market contagion scenario, speculative trading and noise trading may well occur at an international financial level.

markets operating procedures and the growing international diversification of portfolios may facilitate the development of bouts of herding behaviour. In a successive paper Calvo and Mendoza (1997) point out that as the number of markets grows and the share of a given country's assets in the portfolio declines, the payoff from gathering information dwindles while incentives for herding mount.

Rigobon (1998) reintroduces market rationality and attributes the herding behaviour of international investors to the declining quality of price signals, which tend to be distorted over time as a boom or recession is set in motion. The interaction of informed and uninformed rational investors is used by Calvo (1999) to explain the leading role of the main financial centres in spreading the virus. Uninformed investors may, in fact, misread the signal coming from the action of specialists located in the main centres. For example, the latter may be forced to sell emerging-market securities to meet margin calls, while uninformed agents may take this as a signal of expected low returns in the emerging markets and act accordingly.

Kodres and Pritsker (1999) attribute apparent contagion-like market behaviour to rational portfolio managers trying to hedge macroeconomic risk across markets. They show that international market spillovers may occur in the absence of any relevant news or even of direct common linkages across countries. Indeed, a negative shock to one country can lead informed investors to sell that country's assets and buy assets of a second country, increasing their exposure to this country's macroeconomic risk. Investors can then hedge this purchase by selling (or buying) the assets of a third country and generate an apparently erratic spillover from first- to third-country assets. Uninformed investors may attribute the observed price changes to informed investors' speculative trading. Information asymmetries of this kind become more relevant in periods of turbulence, facilitating the spread of contagion-like behaviour.⁵

It is difficult to draw an empirical distinction between these different explanations of contagion. Using daily price index data, rational and irrational interpretations are observationally equivalent. Market microstructure analysis would probably provide useful additional information. *A priori* one would presume that herding behav-

⁵ Information on credit sources becomes more valuable as more companies are budget constrained, accentuating the distorsive effects of information asymmetry.

our in periods of market tension be more likely in the linkages across South American markets and some Asian markets than in those involving European markets. If it is possible to detect the presence of contagion using the VAR methodology described below, it is not easy to determine its nature.

2. The data

The sample period extends from 6 July 1992 to 5 July 1999 (7 years) and has been partitioned in two sub-periods, from 6 July 1992 to 30 May 1997 and from 1 June 1997 to 5 July 1999, to take into account the inception of the crisis in Asia. A dummy variable is used in order to condition for the Mexican crisis.

The data set includes closing daily prices from twelve major national stock markets selected according to both economic and geographical criteria. The Morgan Stanley Capital International (MSCI) close price indexes can be listed as follows: the US stock market index, the British, German, French and Swiss European indexes, the Brazilian, Mexican and Argentinean Latin American indexes and the Japanese, Hong Kong, Taiwanese and Korean Asiatic indexes.⁶ They correspond with few exceptions to relevant centres of international financial intermediation and have, in their respective geographical areas, the largest capitalisation. Tables 1 and 2 provide some preliminary information on the behaviour of the daily stock market returns in the two sub-periods of interest.⁷

According to Table 1, there are consistent departures from normality due mostly to a high level of kurtosis. Indeed, the Jarque Bera tests rule out normality for all the series in both periods. In most cases the series fail to be i.i.d. as shown by the values of the LB Q-statistics, whose high figures for absolute returns and squared returns

⁶ The combined market capitalisation of the companies used to compute the indexes represents approximately 60% of the aggregate market value of the respective stock exchanges.

⁷ Daily returns r_t are calculated as the percentage logarithmic difference in daily stock index prices,

$$r_t = 100 (\log P_t - \log P_{t-1}).$$

[Insert Table 1 here]

may indicate the presence of volatility clustering. Serial correlation of the squared US and European returns rises in the second sub-period and seems to justify the hypothesis of a regime shift. The serial correlation of some European market returns rises too, signalling a possible decrease in efficiency. Serial correlation of market returns may be spurious, however, and in fact caused by asynchronous or discontinuous trading (see Lo and MacKinlay 1990, and Susmel and Engle 1994).

As for the mean and standard deviation, the two periods under examination differ greatly. During the calm period stock-price indexes in the most developed markets (including Japan) are growing, on average, at a rate of about 0.05% per day, the East Asian markets (excluding Japan) at 0.04% per day, while the Latin American countries display more heterogeneous behaviour. Brazil's returns may be considered an exception and are strongly affected by the hyperinflation of the early '90s. During the 'turbulent' period, daily returns in most of the East Asian countries fall dramatically, the Hong Kong index declining by a daily 0.01%. A sharp reduction in returns is also observable for all the Latin American countries but Mexico. Surprisingly, and apart from Japan whose daily returns are zero on average, the group of the developed countries nearly doubles its rate of return, up to more than 0.08% per day on average.

Similarly the standard deviation of the daily returns, which proxies the (unconditional) volatility, displays a different behaviour in the two sub-periods. In the first sub-period developed markets have an average volatility of less than 1%, surging to 1.5% in the second. The same pattern is exhibited by the volatility of the Latin American group, rising from 2 to 2.5%, and by that of the Asian group, soaring from 1.4% in the calm period to 2.5% in the turbulent conjuncture.

Correlation indexes for daily returns are given in Table 2. It is well known that neither causality nor contagion inferences can be drawn from correlation indexes as they merely provide a rough measure of returns interdependence. Several patterns are immediately evident, beginning with the presence of significant market cross correlations during the calm period, which is not surprising, US returns being fairly correlated with returns in Latin America and Europe. Countries belonging to the same geographical area are relatively more interconnected, although Japanese returns tend to be isolated from their own geographical area and linked to European returns. Sec-

only, market cross correlations tend to be higher during the turbulent period.⁸ The increase is generalised. Correlation with US returns moved, on average, from 0.14 to 0.33, and the rise in correlation indexes between the emerging areas and Europe is even sharper. Thirdly, the upsurge of cross correlation coefficients is striking when it involves off-regional markets.

The VAR analysis below was performed using absolute returns, introduced here as a proxy of stock market volatility. Major gains are obtained from the reduction of kurtosis and skewness, which are, on average, a fifth of the values obtained for the squared returns.⁹ The stationarity of the data is examined using standard ADF tests for unit roots. The null hypothesis of unit root is in all cases rejected at 1% level of significance.

3. Measuring volatility linkages: VAR specification of absolute returns

In order to analyse short term stock market interdependence a vector autoregressive (VAR) approach is called for. This is useful as it recognises the endogeneity of all variables in the system and allows for the presence of lagged impacts. Moreover, it investigates the impulse responses to shocks in each market and the related variance decomposition. The methodology has been used in previous studies by Eun and Shim (1989) and Von Furstenberg and Jeon (1989) to analyse the links between the daily returns of some major equity markets across the 1987 crisis. Mills and Mills (1991) applied it to examine the international transmission of daily bond price changes while Koch and Koch (1991) and Peirò, Quesada and Uriel (1998) used it to investigate the effect of trading time overlapping on stock return cross market interlinkages. These studies, however, generally fail to recognise that na-

⁸ Similarly, Calvo and Reinhart (1996) and Baig and Goldfajn (1998) find that international correlations between emerging market stock returns tend to rise during a major crisis.

⁹ The results are not reported here because of lack of space. Absolute returns are used as volatility indexes by Akgiray (1989), West and Cho (1992) and West, Edison and Cho (1993) among others.

tional financial markets may be linked via their variances as well as their means, and that volatility and volatility interdependence may vary over time.

In order to identify the pattern of interdependence among stock market volatilities at both the regional and the worldwide level, we apply the VAR methodology to absolute stock market daily returns.¹⁰

Sims's (1980) VAR approach involves a N variables dynamic equations system with no *a priori* restrictions on the relationships between the variables of interest.

$$Y_t = c + A_1 Y_{t-1} + A_2 Y_{t-2} + \dots + A_p Y_{t-p} + e_t \quad (1)$$

where Y_t is here a $N \times 1$ column vector of daily absolute stock market price index returns; A_1, \dots, A_p are $N \times N$ matrices of coefficients; p is the system's order and e_t is a $N \times 1$ column vector of forecast errors of the Y_t using all past Y_{t-p} .

The VAR(p) process (1) is assumed to be covariance-stationary and thus has vector moving average (VMA) representation

$$Y_t = E(Y) + \sum_{s=0}^{\infty} \phi_s e_{t-s} \quad (2)$$

where the i^{th} element of the $N \times 1$ vector Y_t represents the i^{th} national market's absolute return at period t as a linear least squares projection on past absolute returns of all markets of the system and ϕ_s is a $N \times N$ symmetric variance-covariance matrix of reaction coefficients to the innovations e_{t-s} .

We estimate four VAR systems. Three systems are estimated imposing a hierarchical structure (i.e. including the US) to cover the three regional areas of interest. In addition we run a VAR for five countries (US, Japan, UK, Germany and Brazil) to assess the possible worldwide nature of the contagion. An accurate analysis of the Akaike Information and Schwarz criteria suggests that – in both time periods under investigation – VAR systems of order five provide the

¹⁰ Volatility interlinkages can be analysed using alternative techniques. Hamao, Masulis and Ng (1990) and Bae and Karolyi (1994) have investigated volatility links across international stock markets using GARCH models which point out that the volatility of a given market depends upon the volatility of a previously open foreign one. Theodossiou and Lee (1993) and Koutmos and Booth (1995) have reformulated this line of research in terms of multivariate symmetric and asymmetric GARCH respectively. Karolyi (1995) and Cifarelli and Giannopoulos (1999) use combinations of VAR and GARCH techniques.

best results. For all systems, and across all the sub-periods, we find evidence of volatility linkages across markets. Cross-market coefficients, although biased by the presence of near-collinearity in the systems (Canova 1995), are strongly significant also after correcting for heteroskedasticity.¹¹

Table 3 sets out summary statistics on the (unadjusted) residuals of the four systems under investigation in the two time periods of interest, i.e. from 6 July 1992 to 30 May 1997 and from 1 June 1997 to 5 July 1999. The respective distributions are characterised by significant levels of skewness and kurtosis that seem incompatible with the hypothesis of normality. In the same way, LB Q-statistics consistently reject the null hypothesis that the squared residuals be serially uncorrelated and suggest the presence of heteroskedasticity. Non-normality and heteroskedasticity might distort the estimates of the confidence bands which are used to draw inferences on the significance of the impulse responses.¹²

In order to improve the quality of the estimates, we fitted to each residual either a GARCH(1,1) or a QGARCH(1,1) model *à la* Sentana (1995) and used it as a filter.¹³ As can be seen from the adjusted statistics – given in Table 3 below the corresponding unadjusted ones – the standardized residuals are consistently closer to homoskedasticity and to normality. Subsequent analyses were therefore performed using the standardized residuals.

We implement simulation techniques to perform the standard impulse response and variance decomposition investigations. These techniques require that the (standardized) residual vector be transformed into a vector of orthogonal innovations. Indeed, even if the elements of this vector are serially uncorrelated by construction, there is no guarantee that its contemporaneous components will be uncorrelated as well. The problem is solved with the help of Choleski fac-

¹¹ Due to limited space the estimates are not reported here, but are available upon request to the authors.

¹² The Monte Carlo integration procedure set out in RATS (Doan 1992) is based on a result by Kloek and Van Dijk (1978) which postulates i.i.d. normally distributed residuals. For more details – if the alternative delta method procedure is used to compute the confidence bands – see Lütkepohl (1990, proposition 1 and section II [ii]).

¹³ As usual the standardized residual time series v_{it} is computed as $v_{it} = e_{it}/(h_{it})^{0.5}$, where e_{it} is the i^{th} entry of the $N \times 1$ VAR(p) residual vector, e_t and h_{it} is the corresponding GARCH(1,1) (or QGARCH(1,1)) conditional variance estimate.

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TABLE 3

MEASURE OF ADJUSTMENT OF THE VAR RESIDUALS

torisation of the variance-covariance matrix of the residuals, here depending upon the ordering of the variables listed in the vector Y_t .

The following causal orderings were selected for the VAR systems under investigation:

- World: US, Japan, UK, Germany and Brazil;
- Europe: US, UK, Germany, France and Switzerland;
- Asia: US, Japan, Hong Kong, Taiwan and Korea;
- South America: US, Brazil, Mexico and Argentina.¹⁴

The US market has always been positioned at the top of the causal hierarchy because of its share in world market capitalisation and its crucial influence on international financial markets mood. A battery of Granger causality tests was performed in order to determine a pyramid of causality order among the variables of each VAR system. In spite of adjustment for the different time zones, following the approach of Malliaris and Urrutia (1992), these tests fail to provide clear-cut ranking of national stock markets based upon absolute returns causality.¹⁵ The Japanese market is placed second in the World and Asian systems because of its sheer size and of the major role it played in transmission of the recent turbulence across the Pacific Basin countries. The British market is placed third in the World system and second in the European one. It holds a leading position in transmitting investment opportunities between Europe and the US thanks to a liberal legislation and is the third largest in terms of capitalisation. In each VAR system the hierarchy of the remaining stock markets was determined according to their ordering in terms of World index capitalisation.

Time lags are synchronised in order to take into account the differing trading times and reproduce realistic transmission of news across markets. Our data set includes daily close to close returns for

¹⁴ A Monday-effect dummy was included as explanatory variable in the regressions of the World, Europe and Asia VAR systems. An additional dummy variable, designed to account for the Mexican crisis, enters the equations of the World and Latin America systems in the first sub-period (1992-97).

¹⁵ The rank ordering does not seem to incur significant distortions. Preliminary results using the 'generalised impulse approach' of Koop, Pesaran and Potter (1996), which is invariant to the ordering of the variables in the VAR, provides analogous response profiles.

national markets generally operating in successive time zones with different opening and closing times as shown by Table 4. The first column reports the trading hours in local time; the second column translates them into GMT time. Every trading day the Asian returns for that day are known when the US, European and South American markets open. They can be seen as predetermined and are included with lags from zero to four in the US, European and Brazilian returns equations of the VAR(5) systems. As noted by Koch and Koch (1991), this “block recursivity” holds even though the 24-hour periods used to compute close to close returns overlap over time.

TABLE 4

TRADING HOURS

	Local Time	GMT
New York	9.30-16.00	14.30-21.00
Tokyo	9.00-11.00 // 12.30-15.00	0.00-2.00 // 3.30-6.00
London	8.30-16.30	8.30-16.30
Frankfurt	8.30-17.00	7.30-16.00
Paris	10.00-17.00	9.00-16.00
Zürich	9.00-17.00	8.00-16.00
Hong Kong	10.00-12.30 // 14.30-16.00	2.00-4.30 // 6.30-8.00
Taipei	9.00-12.00	1.00- 4.00
Sao Paulo	11.00-18.00	14.00-21.00
Seoul	9.00-12.00 // 13.00-15.00	0.00-3.00 // 4.00-6.00
Mexico C. Mexico	8.30-15.00	14.30-21.00
Buenos Aires	11.00-18.00	14.00-21.00

Source: <http://www.FIBV.com>.

European markets are still trading when the US and Latin American markets open. Their returns are treated as predetermined, however, and included with lags from zero to four in the US and Brazilian returns relationships since – as pointed out by Booth *et al.* (1997) – at market opening time US traders are privy to almost 80% of their daily behavior. The parameterisation of the VAR models used in the estimation is set out in the Appendix.

4. Measuring volatility spillovers: impulse response and variance decomposition analysis

The four autoregressive systems are estimated in the two relevant time periods. The corresponding impulse response and variance decomposition analyses are then performed in order to identify the effects of the recent international stock market turbulence. In each system the orthogonalized variance-covariance matrix of standardized vector autoregressive residuals is used. As suggested by Runkle (1987), confidence bands are computed to provide a statistical foundation for impulse responses analysis. Standard errors are calculated using the Monte Carlo integration procedure set out in RATS (Doan 1992).

4.1. *Impulse response analysis*

Figures 1 to 8 show the time path of each market's dynamic response to every other market innovations in the four systems under investigation. Each graph displays the response of one stock market to a one-standard deviation shock in a variable of the system, which could also be a shock to itself. The label on the left-hand side of each row of the charts indicates the market where an innovation has occurred and the plots of the charts of this row show the dynamic response of each market to this innovation. The response is the middle line while the upper and lower bounds indicate the confidence bands. Thus an impulse value other than zero, with a probability of at least 95%, is given by the confidence band that is closer to the horizontal axis. Hence, if at any period the horizontal axis lies inside the upper and lower confidence bands, then the corresponding impulse response is zero.

During the first period – from 6 July 1992 to 30 May 1997 – the US, British, and Japanese stock markets are insensitive to innovations from other markets.

The Latin American and European markets are highly sensitive to news from the US, the leading market in the sample. Responses in Brazil (Figures 1 and 7) are negative – an unusual result that may,

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however, be interpreted in the context of the 1995 crisis.¹⁶ Inter-regional spillovers are mostly significant and Argentina seems to be the most reactive to foreign news.

The time it takes for a country's volatility to return to normal may be considered an index of relative efficiency. In the Latin American countries the impact of the shocks tends to disappear (with few exceptions) in five to eight days, which is a little longer than in the other countries under investigation. In Europe (Figure 3) the duration of the responses does not go beyond a single trading day.

The pivotal role of the UK (Figures 1 and 3) is exemplified by its immunity from other markets' shocks and its ability to transfer volatility across the European and Brazilian stock exchanges. European interlinkages are numerous, possibly because of the rapid growth of some of the financial markets of the system.¹⁷

In Asia, surprisingly, US volatility affects only the Hong Kong stock exchange (Figure 5). As for Japan, its isolation is almost complete, as there are no significant volatility connections with other markets in the area. Japan's puzzling isolation also emerges in Ito and Lin (1993), who fail to detect volatility spillovers between the New York and Tokyo stock markets using intraday data. Analogous findings are obtained in Karolyi and Stulz (1996), who ascertain that cross-correlation between the US and Japanese equity markets is not sensitive to shocks in fundamental variables.

The impulses of the VAR systems change in the second 'turbulent' period and share the following characteristics: *i*) the US market plays a dominant role in the diffusion of news, growing in Asia and declining in Europe; *ii*) the dimension and the number of volatility

¹⁶ During the Mexican crisis capitals moved from Latin America towards safer markets (financial flows from Latin American countries towards the US rose from 41 billion dollars in 1994 to 95 billion in 1995). A jolt in the volatility of the US market generates a perception of higher risk and causes portfolio readjustments back into Brazilian stocks. The resulting Brazilian equity price increases offset the price decreases of other local stocks due to the bad news (the increase in volatility) coming from the US. The net result, on average, is an overall reduction in the rate of change of the Brazilian stock market price index. This repatriation effect may explain the negative correlation between US volatility and the volatility of markets in countries whose residents invest heavily in US assets. A similar reasoning is usually applied also to Japan.

¹⁷ Karolyi (1995) suggests that an increase in international financial integration should reduce stock market volatility interdependence. A market size effect, however, could offset the efficiency effect and raise the dimension of the spillovers.

FIGURE 2

spillovers increase; *iii*) the accuracy of the impulse estimates does not, however, decline as the width of confidence bands remains mostly unaltered. The first two characteristics may be interpreted as symptoms of contagion across equity markets.

US isolation is broken by the British and German innovations (Figure 2). In Latin America (Figure 8) the Asian crisis reduces market efficiency and tends to raise the dimension and the persistence of the volatility impulses across markets. In Europe (Figure 4), the crisis alters the role of the German market, whose volatility spillovers with the US are now bi-directional. In Asia (Figure 6) stock markets become more sensitive to US news; contagion does not seem to be a regional phenomenon and it radiates from US market volatility. Japan does not seem to play a dominant role during the crisis, contradicting our *a priori* belief.

In brief, it clearly emerges that the mechanism of volatility transmission between markets may vary over time.

4.2. Variance decomposition analysis

To provide more details on the speed and source of volatility transmission, VAR innovations accounting for each system and in the two sub-periods is set out in Table 5. The eight small tables correspond to the variance decomposition of the four VAR systems under investigation prior to and during the Asian crisis. In each table a given row shows the evolution over 1, 5 and 20 trading days of the fractions of variance of the volatility of one market that can be attributed to simulated shocks in the volatility of the markets that are listed at the top of each column.

These results indicate that during the calm period most of the innovation adjustment is completed within five days. The US, British and Japanese markets appear to be virtually unaffected by the other markets, seeming to depend only on their own past volatilities. The US market provides a concrete explanation for the forecast error variance of the Hong Kong, European and Latin American stock markets. For instance, on a 5-day horizon the US contributes to 9.01% of the forecast error variance in Germany, 12.20% in Brazil and 17.70% in Hong Kong.

Inserire Tabella 5

FIGURE 3

FIGURE 4

While favouring the inception of new inter-regional linkages, the turmoil of the second sub-period appears to have affected both the innovation adjustment time and the role of the main financial centres. The share of foreign innovations in the volatility forecast error variances tends to increase in the four VAR systems and, conversely, the share of own innovations tends to decline. This pattern seems to be compatible with the hypothesis of volatility contagion across markets.

The time to complete innovation adjustment increases from 5 to 10-11 days in the emerging areas. The role played by the leading centres in transmitting volatility across national markets and regional areas is reinforced. In the World and Europe VAR systems, Great Britain and (to a lesser extent) Germany play a growing role and tend to overtake the US. Innovations from the US and Japan account for a greater fraction of the volatility of the remaining countries of the Asia VAR, and innovations from the US play a pivotal role in the transmission of news in the Latin America VAR. News from the US explain up to 0.75, 18.20 and 0.91% of the volatility variance of Korea, Hong Kong¹⁸ and Taiwan before the Asian crisis and, respectively, 8.78, 30.90 and 5.06% during the crisis. In Latin America the increase in US influence is even more striking as the share of Mexican volatility accounted for by US news after four weeks jumps from 5.08 to 24.50%. On the whole, the Asian markets seem to retain a lesser degree of interdependence during the crisis than the Latin American ones.

Variance decomposition analysis suggest that volatility spillovers across international markets follow a geographical hierarchy, and gives support to the hypothesis of a regime shift in the transmission of volatility.

5. Conclusions

This paper does not attempt to investigate the origin and extent of the Asian crisis or the sources of financial contagion, the aim being to assess if and how the crisis impinges on stock market volatility linkages

¹⁸ A result that may be due to the presence of the currency board.

FIGURE 5

FIGURA 6

and whether the contagion is of a regional or a worldwide nature. Four VAR systems were estimated using the absolute value of the stock returns as volatility indexes in order to minimise distortions due to non-normality and heteroskedasticity. They were constructed by imposing a geographical hierarchy (the US is included in each area under investigation) and modified appropriately in order to adjust for differences in trading times.

By simulating the way innovations in national volatilities influence foreign stock markets, the VAR methodology makes it possible to detect volatility transmission from one market to another as well as its persistence. As inference based on impulse response and variance decomposition analyses relies on normal i.i.d. residuals, the VAR errors were filtered with GARCH models, substantially improving the results.

The Asian crisis suggests that, during periods of financial market instability, market participants tend to move together across countries. Crises are in fact characterised by clusters of bad news that may increase uncertainty, thus accentuating the herding behaviour. Econometric analysis provides evidence of a generalised increase in volatility and discernible differences in the contagion pattern during the turbulent period.

Changes are observable in the Asian area where new linkages are formed, whereas spillovers in Latin America are magnified. Inside each geographical area, own innovations account for a significantly smaller part of the national forecast error variance and few regional market shocks have the virulence to affect the volatility of off-regional stock exchanges. European markets are strongly affected by the regime shift; and indeed in the second period all the innovations originated by countries in the area have an impact on the volatility of the other major financial centres. The leading role of the US is maintained although its isolation is interrupted by British and German innovations.

A hierarchy among financial markets does, however, distinctly emerge. In both time periods under investigation innovations in other markets have little or no effects on the US, Japanese and British markets, standing as the leading stock markets of the sample. These results are suggestive of a pyramidal (hierarchical) contagion pattern.

Large markets become more influential in periods of turbulence. Two tentative explanations of this shift are prompted: 1) a herding ef-

FIGURA 7

FIGURA 8

fect, as investors in secondary markets tend to imitate the behaviour of their counterparts in the leading markets and *ii*) a ‘hot potato’ explanation. In periods of uncertainty the assets traded in small, relatively recent markets affected by a significant country risk are sold first and tend to pass from one portfolio to the other.

APPENDIX

World – VAR System

$$\begin{aligned}
 US_t &= a^{us} + \sum_{i=1}^5 a_{1i}^{us} US_{t-i} + \sum_{i=0}^4 a_{1i}^{jp} JP_{t-i} + \sum_{i=0}^4 a_{1i}^{uk} UK_{t-i} + \sum_{i=0}^4 a_{1i}^d D_{t-i} + \sum_{i=1}^5 a_{1i}^{br} BR_{t-i} + e_t^{us} \\
 JP_t &= a^{jp} + \sum_{i=1}^5 a_{2i}^{us} US_{t-i} + \sum_{i=1}^5 a_{2i}^{jp} JP_{t-i} + \sum_{i=1}^5 a_{2i}^{uk} UK_{t-i} + \sum_{i=1}^5 a_{2i}^d D_{t-i} + \sum_{i=1}^5 a_{2i}^{br} BR_{t-i} + e_t^{jp} \\
 UK_t &= a^{uk} + \sum_{i=1}^5 a_{3i}^{us} US_{t-i} + \sum_{i=0}^4 a_{3i}^{jp} JP_{t-i} + \sum_{i=1}^5 a_{3i}^{uk} UK_{t-i} + \sum_{i=1}^5 a_{3i}^d D_{t-i} + \sum_{i=1}^5 a_{3i}^{br} BR_{t-i} + e_t^{uk} \\
 D_t &= a^d + \sum_{i=1}^5 a_{4i}^{us} US_{t-i} + \sum_{i=0}^4 a_{4i}^{jp} JP_{t-i} + \sum_{i=1}^5 a_{4i}^{uk} UK_{t-i} + \sum_{i=1}^5 a_{4i}^d D_{t-i} + \sum_{i=1}^5 a_{4i}^{br} BR_{t-i} + e_t^d \\
 BR_t &= a^{br} + \sum_{i=1}^5 a_{5i}^{us} US_{t-i} + \sum_{i=0}^4 a_{5i}^{jp} JP_{t-i} + \sum_{i=0}^4 a_{5i}^{uk} UK_{t-i} + \sum_{i=0}^4 a_{5i}^d D_{t-i} + \sum_{i=1}^5 a_{5i}^{br} BR_{t-i} + e_t^{br}
 \end{aligned}$$

Europe – VAR System

$$\begin{aligned}
 US_t &= b^{us} + \sum_{i=1}^5 b_{1i}^{us} US_{t-i} + \sum_{i=0}^4 b_{1i}^{uk} UK_{t-i} + \sum_{i=0}^4 b_{1i}^d D_{t-i} + \sum_{i=0}^4 b_{1i}^{ff} FF_{t-i} + \sum_{i=0}^4 b_{1i}^{sw} SW_{t-i} + e_t^{us} \\
 UK_t &= b^{uk} + \sum_{i=1}^5 b_{2i}^{us} US_{t-i} + \sum_{i=1}^5 b_{2i}^{uk} UK_{t-i} + \sum_{i=1}^5 b_{2i}^d D_{t-i} + \sum_{i=1}^5 b_{2i}^{ff} FF_{t-i} + \sum_{i=1}^5 b_{2i}^{sw} SW_{t-i} + e_t^{uk} \\
 D_t &= b^d + \sum_{i=1}^5 b_{3i}^{us} US_{t-i} + \sum_{i=1}^5 b_{3i}^{uk} UK_{t-i} + \sum_{i=1}^5 b_{3i}^d D_{t-i} + \sum_{i=1}^5 b_{3i}^{ff} FF_{t-i} + \sum_{i=1}^5 b_{3i}^{sw} SW_{t-i} + e_t^d \\
 FF_t &= b^{ff} + \sum_{i=1}^5 b_{4i}^{us} US_{t-i} + \sum_{i=1}^5 b_{4i}^{uk} UK_{t-i} + \sum_{i=1}^5 b_{4i}^d D_{t-i} + \sum_{i=1}^5 b_{4i}^{ff} FF_{t-i} + \sum_{i=1}^5 b_{4i}^{sw} SW_{t-i} + e_t^{ff} \\
 SW_t &= b^{sw} + \sum_{i=1}^5 b_{5i}^{us} US_{t-i} + \sum_{i=1}^5 b_{5i}^{uk} UK_{t-i} + \sum_{i=1}^5 b_{5i}^d D_{t-i} + \sum_{i=1}^5 b_{5i}^{ff} FF_{t-i} + \sum_{i=1}^5 b_{5i}^{sw} SW_{t-i} + e_t^{sw}
 \end{aligned}$$

Asia – VAR System

$$\begin{aligned}
 US_t &= c^{us} + \sum_{i=1}^5 c_{1i}^{us} US_{t-i} + \sum_{i=0}^4 c_{1i}^{jp} JP_{t-i} + \sum_{i=0}^4 c_{1i}^{hk} HK_{t-i} + \sum_{i=0}^4 c_{1i}^{tw} TW_{t-i} + \sum_{i=0}^4 c_{1i}^{kr} KR_{t-i} + e_t^{us} \\
 JP_t &= c^{jp} + \sum_{i=1}^5 c_{2i}^{us} US_{t-i} + \sum_{i=1}^5 c_{2i}^{jp} JP_{t-i} + \sum_{i=1}^5 c_{2i}^{hk} HK_{t-i} + \sum_{i=1}^5 c_{2i}^{tw} TW_{t-i} + \sum_{i=1}^5 c_{2i}^{kr} KR_{t-i} + e_t^{jp} \\
 HK_t &= c^{hk} + \sum_{i=1}^5 c_{3i}^{us} US_{t-i} + \sum_{i=1}^5 c_{3i}^{jp} JP_{t-i} + \sum_{i=1}^5 c_{3i}^{hk} HK_{t-i} + \sum_{i=1}^5 c_{3i}^{tw} TW_{t-i} + \sum_{i=1}^5 c_{3i}^{kr} KR_{t-i} + e_t^{hk} \\
 TW_t &= c^{tw} + \sum_{i=1}^5 c_{4i}^{us} US_{t-i} + \sum_{i=1}^5 c_{4i}^{jp} JP_{t-i} + \sum_{i=1}^5 c_{4i}^{hk} HK_{t-i} + \sum_{i=1}^5 c_{4i}^{tw} TW_{t-i} + \sum_{i=1}^5 c_{4i}^{kr} KR_{t-i} + e_t^{tw} \\
 KR_t &= c^{kr} + \sum_{i=1}^5 c_{5i}^{us} US_{t-i} + \sum_{i=1}^5 c_{5i}^{jp} JP_{t-i} + \sum_{i=1}^5 c_{5i}^{hk} HK_{t-i} + \sum_{i=1}^5 c_{5i}^{tw} TW_{t-i} + \sum_{i=1}^5 c_{5i}^{kr} KR_{t-i} + e_t^{kr}
 \end{aligned}$$

Latin America – VAR System

$$\begin{aligned}
US_t &= d^{us} + \sum_{i=1}^5 d_{1i}^{us} US_{t-i} + \sum_{i=1}^5 d_{1i}^{br} BR_{t-i} + \sum_{i=1}^5 d_{1i}^{mx} MX_{t-i} + \sum_{i=1}^5 d_{1i}^{ar} AR_{t-i} + e_t^{us} \\
BR_t &= d^{br} + \sum_{i=1}^5 d_{2i}^{us} US_{t-i} + \sum_{i=1}^5 d_{2i}^{br} BR_{t-i} + \sum_{i=1}^5 d_{2i}^{mx} MX_{t-i} + \sum_{i=1}^5 d_{2i}^{ar} AR_{t-i} + e_t^{br} \\
MX_t &= d^{mx} + \sum_{i=1}^5 d_{3i}^{us} US_{t-i} + \sum_{i=1}^5 d_{3i}^{br} BR_{t-i} + \sum_{i=1}^5 d_{3i}^{mx} MX_{t-i} + \sum_{i=1}^5 d_{3i}^{ar} AR_{t-i} + e_t^{mx} \\
AR_t &= d^{ar} + \sum_{i=1}^5 d_{4i}^{us} US_{t-i} + \sum_{i=1}^5 d_{4i}^{br} BR_{t-i} + \sum_{i=1}^5 d_{4i}^{mx} MX_{t-i} + \sum_{i=1}^5 d_{4i}^{ar} AR_{t-i} + e_t^{ar}
\end{aligned}$$

$US_t, JP_t, UK_t, D_t, FF_t, SW_t, HK_t, TW_t, KR_t, BR_t, MX_t$ and AR_t indicate the time t absolute returns of the US, Japanese, British, German, French, Swiss, Hong Kong, Taiwanese, Korean, Brazilian, Mexican and Argentinean stock market indexes, respectively. The dummies mentioned in the text are not reported here.

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