Dynamic conditional correlation analysis of financial market interdependence

Kuper, Gerard H.; Lestano, [No Value]

CCSO Centre for Economic Research

University of Groningen

CCSO Working Papers **April, 2006**

CCSO Working paper 2006/02

Dynamic conditional correlation analysis of financial market interdependence: An application to Thailand and Indonesia

Gerard H. Kuper
Department of Economics, University of Groningen

Lestano
Department of Economics, University of Groningen

CCSO Working Papers
http://www.eco.rug.nl/ccso

Dynamic conditional correlation analysis of financial market interdependence: An application to Thailand and Indonesia

Gerard H. Kuper* and Lestano
Department of Economics, University of Groningen

April 2006

Abstract

This paper examines the dynamic linkages among financial markets in Thailand and Indonesia. In particular, we focus on the cross-border relationship in individual markets and on the relationship between financial markets within each country. We find that while tight monetary policy pursued by Thailand authorities helped to defend the exchange rate at the outbreak of the financial crisis, it had little consequences for Indonesia at the end of 1998. The correlations between countries within each of the financial market reveals a certain degree of interdependence among countries, which is lower during crises.

Keywords: currency crises, dynamic conditional correlation, interdependence
JEL-code: F31, F47

*Corresponding author: Gerard H. Kuper, Department of Economics, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands. Tel.: +31 50 363 3756. Fax: +31 50 363 7337. Email: g.h.kuper@rug.nl

1 Introduction

The Asian currency and financial crisis of the 1990s represents perhaps the most significant economic event of this kind since the Great Depression. The massive devaluation of the Thailand baht in July 1997 led to similarly dramatic devaluations in exchange rates in Indonesia, Malaysia, the Philippines, and South Korea. In these countries, authorities were forced to raise interest rates to prevent a run on their currencies and stock prices reached historical lows. Next, Hong Kong and Taiwan were affected, putting pressure on their currencies and sharply depressing local stock markets. The first bout of truly global contagion then ensued, as stock markets in the United States and Europe dropped sharply. A description of these events can be found in International Monetary Fund (1998), Goldstein (1998), Corsetti et al. (1999), and Chowdhry and Goyal (2000).

This paper attempts to throw light on the relationship among financial markets in Thailand and Indonesia. Thailand is regarded as the ground–zero country where the severe speculative attack began while Indonesia is one of the countries that were hit in subsequent periods. We first draw attention to the linkages between exchange rates, interest rates, and stock market returns in individual countries. The relation between exchange rates and interest rates is of considerable interest to find evidence whether monetary tightening, as part of the IMF-supported programs, was successful in defending the exchange rate from speculative pressures during the Asian financial crisis. In addition, it is important to understand the link between stock prices and exchange rates and interest rates, especially in the case of high volatility and unstable markets, which are typical in emerging economies such as Thailand and Indonesia. Second, we focus on cross-border relationships in each financial market to understand financial market synchronisation and integration. This issue is crucial since greater integration implies stronger co-movements between markets which can also lead to contagion across markets, therefore reducing the opportunities for international diversification.

Using daily data on exchange rates, interest rates and stock market returns from March 3, 1995 to December 31, 2001, we estimate a recently proposed representative of the class of multivariate GARCH models, the so-called dynamic conditional correlation (DCC) model (Engle, 2002). Correlations are time-dependent and estimation procedures can handle volatility clustering. There are only a few studies that use DCC models to study financial markets, especially for the emerging markets of Asia. Examples are Bautista (2003) and Yang (2005).

The remainder of the paper is structured as follows. Section 2 describes models which explain the relationship among financial markets. In Section 3 the multivariate GARCH and DCC models are discussed. Section 4 describes the data. We report the estimation results in Section 5 and discuss their implications in Section 6. Section 7 concludes this paper.

2 Financial markets interdependence

Financial markets are linked both within countries and across countries. Empirical studies of foreign exchange or international money markets mostly rely on purchasing power parity or (un)covered interest parity theory, and studies on international linkages between stock market returns are based on the theory of international portfolio diversification. Since the seminal work of Markowitz (1952), modern portfolio theory underlines that not only returns and volatilities are important in the portfolio selection process, but also correlations between assets. Studies on contagion triggered by the Asian financial crisis often use stock market returns, exchange rates, and interest rates to detect contagion and analyse transmission channels. Dungey et al. (2005) reviews and compares various empirical modelling approaches of contagion.

Also within countries financial markets are linked. Economic theory argues that policymakers face a trade-off: letting the exchange rate float implies a fixed cost arising from the possible loss of credibility. This cost reflects the fact that policymakers have to abandon their disinflation goal linked to an exchange rate anchor. In addition, the cost of maintaining the peg is associated with either an output loss, because of an overvalued currency or excess current deficits resulting from it, or with budgetary consequences of higher interest rates needed to defend the currency. This framework has been associated with self-fulfilling currency crises because the relative cost of defending the currency increases substantially during a speculative attack, and policymakers may choose to abandon the peg once the attack occurs.

In case of the Asian financial crisis there has been debate about the relationship between exchange rates and interest rates. The IMF argues that steep rises in interest rates were vital in stabilising the Asian exchange rates and thus encouraging capital inflows. However, a number of economists, including Radelet and Sachs (1998), Furman and Stiglitz (1998) and Stiglitz (1999), argue that interest rate hikes destabilise the currencies further by increasing the risk of bankruptcy of highly leveraged borrowers. These manifest themselves in the form of a larger country risk premium, a lower, possibly negative, expected return to investors, and capital flight—all of which generate downward pressure on the exchange rate. This situation is termed a perverse effect of a tight monetary policy in the economic literature (see also Aghion et al., 2001).

Also theoretical models suggest a causal relationship between stock prices and exchange rates. The monetary models of exchange rate determination take money supply, the interest rate, the price level and inflation into account to predict exchange rate movements. This model provides a robust tool to link stock prices and foreign exchange rates. An alternative model is the portfolio-balance model incorporating portfolios of assets to describe exchange rate movements. According to this model, expectations of financial asset price movements affect exchange rate dynamics with a negative correlation. The finding is supported by Gavin (1989) and Zapatero (1995). The model of Dornbusch and Fischer (1980) shows the opposite line of causality from exchange rates to stock prices. Currency dynamics affect the international competitiveness of firms, thereby influencing output and eventually stock prices, which are interpreted as reflecting the present value of firms' future cash flows. Other studies using exchange rate exposure models reach the same conclusion. For instance, Hekman (1985) proposes a present value based financial valuation model for multinational firms, in which the exchange rate is a leading indicator of the stock price. Sercu and Vanhulle (1992) explore the impact of exchange rate volatility on the market value of firms and conclude that an increase in exchange rate volatility has a positive effect on the market value of firms. The relationships between stock prices and exchange rates have been empirically analysed for the past three decades with mixed results. For a survey we refer to Koutmos and Martin (2003).

According to the so-called Fisher effect nominal interest rate movements maintain a close track to expected inflation movements in order to compensate lenders for changes in the real value of nominal interest rate payments. In the light of the Fisher hypothesis stocks and bonds should be a hedge against inflation. However, nominal interest rates do not move one for one with inflation, because they reflect expectations of future inflation rather than current inflation. By contrast, inflation seems to affect stock prices through an impact on future earnings and through the way investors discount future earnings.

3 Multivariate GARCH and DCC models

Since the seminal article of Engle (1982) traditional time series tools such as autoregressive moving average for the mean have been extended to essentially analogous models for the variance. Univariate autoregressive conditional heteroscedasticity (ARCH) and generalised ARCH (GARCH) models are now commonly used to describe and forecast changes in volatility of financial time series. Surveys of ARCH modelling in general and its widespread use in finance applications can be found in Bollerslev et al. (1992), Bera and Higgins (1993), Bollerslev et al. (1994), or Pagan (1996). More recently, the univariate GARCH model has been extended to multivariate GARCH (MVGARCH), recognising that multivariate GARCH models are potentially useful developments regarding the parameterisation of conditional cross-moments (see Franses and van Dijk, 2000 and Gourieroux and Jasiak, 2001, for surveys). Different classes of MVGARCH models have been proposed in the literature. They differ in the specification of the conditional variance matrix of a stochastic vector process. Bollerslev et al. (1988) propose a diagonal representation in which the variances depend only on one's own past squared errors and covariances on one's own past cross-products of errors. Because it is difficult to guarantee the positivity of the conditional variance matrix in the diagonal representation without imposing restrictions on the parameters, Engle and Kroner (1995) propose a new parameterisation that easily imposes positiveness, i.e., the Baba, Engle, Kraft, and Kroner (BEKK) model.

The difficulty when estimating a diagonal representation or even a BEKK model is the large number of unknown parameters, even after imposing several restrictions. It is therefore not surprising that these models are rarely used when the number of series exceeds three or four. Factor models proposed by Engle et al. (1990) and orthogonal models as put forward by Alexander (2002) circumvent this difficulty by imposing a common dynamic structure on all elements of the conditional variance matrix which results in less parameterised models.

Current MVGARCH modelling uses conditional correlations instead of conditional covariances as described above. The conditional variance matrix for conditional correlation models is specified in a hierarchical way. First, one chooses a model for each conditional variance, like for instance, a conventional GARCH model. Second, based on the conditional variances, one models the conditional correlation matrix. Notice that like the conditional variance matrix, the conditional correlation matrix has to be positive definite at each point in time. Conditional correlation models have the flexibility of univariate GARCH models for the conditional variances. Bollerslev (1990) proposes a class of MVGARCH models in which the conditional correlations are constant and thus the conditional covariances are proportional to the product of the corresponding conditional standard deviations.

The assumption of Bollerslev's (1990) model that the conditional correlations are constant may seem unrealistic in many empirical applications, for example, studies of Longin and Solnik (1995), Tse (2000), Engle and Sheppard (2001) show that correlations are not constant over time. Therefore Engle (2002) and Tse and Tsui (2002) propose a generalisation of Bollerslev's (1990) constant conditional correlation model by making the conditional correlation matrix time-dependent. This type of model is called a dynamic conditional correlation (DCC) model. The DCC approach has convenient practical advantages. The model guarantees that the time dependent conditional correlation matrix is positive definite for each point in time. Moreover, the number of parameters grows linearly and therefore the model is relatively parsimonious. We refer to Engle and Sheppard (2001) for more detail on the DCC models (see also Appendix A).

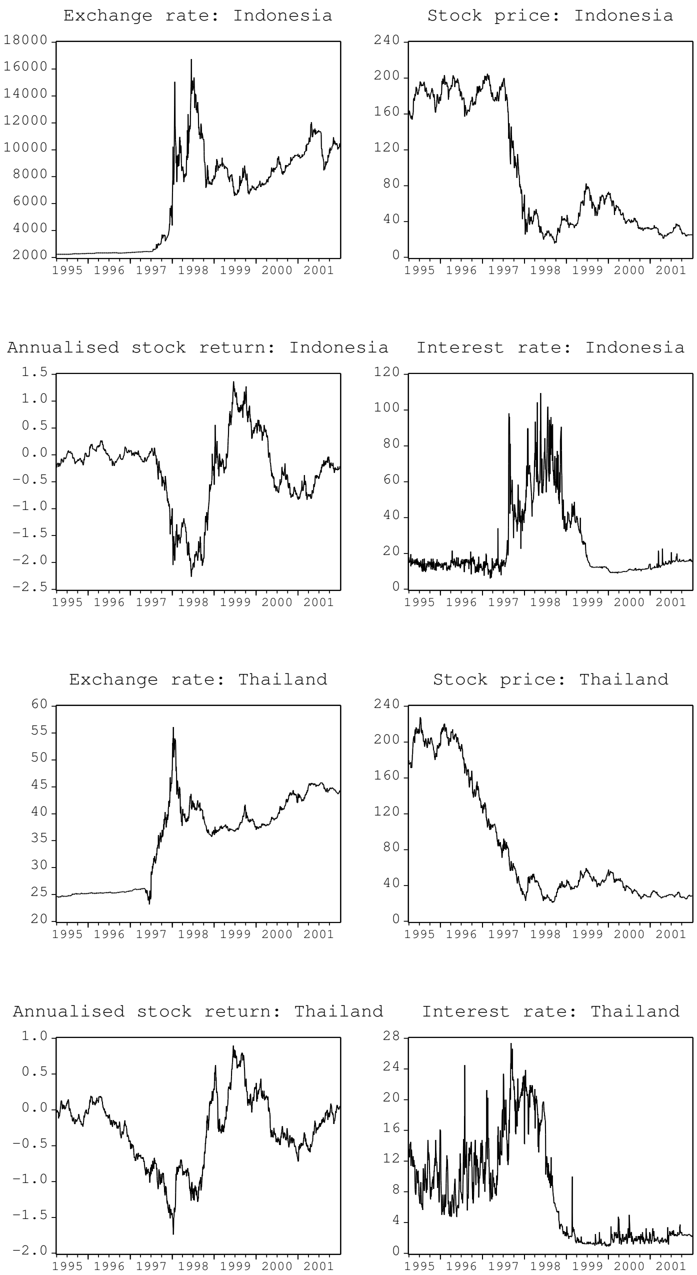
4 Data and properties

In this paper we focus on the stock market, the market for foreign exchange and the money market in Indonesia and Thailand. The latter country is considered the source of the Asian financial crisis outbreak and the first is the most severely affected country in terms of economic and social costs. All data is obtained from Thomson-Datastream and encompasses the period March 3, 1995 to December 31, 2001 for a total of 1,762 observations. Daily data (five days per week) is preferred to lower frequency data such as annual data because low frequency data obscure transient responses to innovations which may last for a few days only. The period of data are chosen to include financial crisis events. We use the exchange rates (national currency per US dollar), the Dow Jones price indices in terms of US dollar[1], and the intercall bank rate, for the money, stock, and foreign exchange market, respectively. The annualised stock returns are defined as the differences between the natural logarithm of the stock price indices on the same day in consecutive years.

Figure 1 plots each series. In general, stock markets in Indonesia and Thailand were stable until 1996 when the Thai market started to crumble. In the following period, all markets plunged as the financial crisis shuddered throughout the region. The magnitude of the negative effect of the Asian crisis in 1997–1998 is huge as Figure 1 clearly indicates. Although the markets have made a decent recovery since then, the market returns remain below the 1990s level. Exchange rate and interest rate figures show a similar pattern during the Asian financial turmoil. The exchange rates of two economies were pegged to the US dollar before the crisis and the rates were occasionally adjusted depending on economic conditions. The outbreak of the financial crisis forced both countries to switch to a floating exchange rate regime. Following episodes of speculative attacks in 1996, the Thai baht came under strong pressure in early 1997 and depreciated until it reached the lowest value against the US dollar in the early months of 1998. The Indonesian exchange rate was affected by this event and a spectacular political change occurred. The rupiah reached its highest level in mid-1998. We use intercall bank interest rates (short-term rates) that monetary authorities often regulate and thus reveal policy intentions more directly. The interest rate figures for both countries show sharp increases in the aftermath of the crisis. Indonesia initially raised interest rates substantially in the middle of 1997 but reduced them subsequently, only raising

[1]The indices measure the price performance but not include income from dividend payments. Note that these payments may contribute to the size of total market returns.

Figure 1: Foreign exchange rates, stock market prices and returns, and interest rates; March 3, 1995–December 31, 2001



Note: Annualised stock market returns are defined as the differences between the natural logarithm of the stock price indices on the same day in consecutive years.

them to higher levels around the beginning of 1998. Thailand increased the interest rate continuously from mid-1997 to almost the end of 1998. This indicates that both economies pursued a quite tight monetary policy to defend their exchange rate during crisis periods. This policy is a reflection of the IMF-supported programs.

Table 1: Descriptive statistics of foreign exchange rates, stock market prices and returns, and interest rates; March 3, 1995–December 31, 2001

	Mean	Median	Std. dev.	Skewness	Kurtosis	Jarque-Bera
Exchange rates						
Indonesia	6,457.94	7,465.00	3,560.26	0.09	1.77	113.90
Thailand	35.37	37.59	7.85	−0.19	1.69	137.05
Stock market prices						
Indonesia	94.04	57.32	68.56	0.47	1.41	250.40
Thailand	82.84	46.17	2.84	0.95	2.25	311.44
Annualised stock market returns						
Indonesia	−0.28	−0.13	0.69	−0.68	3.62	163.23
Thailand	−0.29	−0.22	0.49	−0.27	2.85	22.38
Interest rates						
Indonesia	24.24	14.61	20.44	1.74	5.11	1,212.74
Thailand	7.61	5.88	6.52	0.85	2.58	222.32

Note: The critical value of Jarque-Bera statistic with two degrees of freedom is 5.99.

Table 1 presents descriptive statistics for each financial market. Over the whole sample, Indonesia has a higher mean stock market price, i.e., 94.04 points, compared to Thailand with 82.84 points. Similarly, the mean of the intercall bank rate in Indonesia (24.24%) is higher than in Thailand (7.61%). The mean of the annualised stock market returns is higher for Indonesia (-0.28%) than Thailand (-0.29%). Each series generally appears to follow a non-normal distribution as the Jarque-Bera statistic indicates.

Table 2 reports test results of serial correlation and ARCH effects for all series at 12 and 24 lags. The Ljung-Box Q-statistics at 12 and 24 lags are computed for both the series and squared series. The Q-statistics indicate the presence of significant linear and non-linear dependences. The first type of dependencies may be due to some form of market inefficiency or market structure while autoregressive conditional heteroscedasticity may cause the latter type of dependency. The ARCH tests also support the presence of autoregressive conditional heteroscedasticity. The null hypothesis of no ARCH is clearly rejected at the 5% significance level.

Table 2: Serial correlation and ARCH effect tests of foreign exchange rates, stock market returns, and interest rates; March 3, 1995–December 31, 2001

	Ljung-Box Q-statistics series		Ljung-Box Q-statistics squared series		ARCH-LM series	
	12 lags	24 lags	12 lags	24 lags	12 lags	24 lags
Exchange rates						
Indonesia	99.80	192.21	62.20	86.11	63.12	66.68
Thailand	91.40	120.76	45.86	46.51	71.58	78.23
Stock market returns						
Indonesia	71.34	82.31	44.61	36.56	39.51	70.91
Thailand	64.44	93.91	54.01	61.05	45.68	63.39
Interest rates						
Indonesia	82.00	94.43	57.87	64.67	45.83	57.83
Thailand	128.92	135.83	68.87	96.05	59.31	85.48

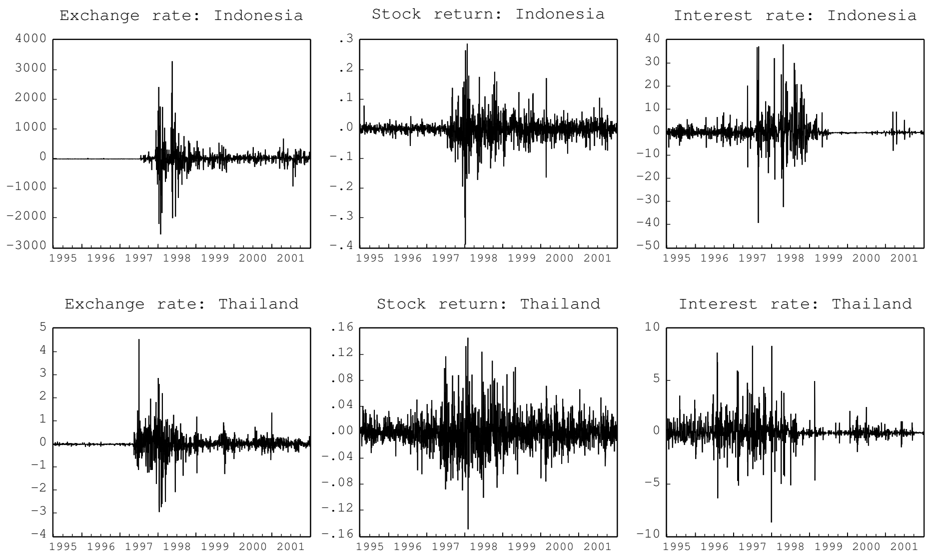
Note: Ljung-Box Q-statistic tests the null hypothesis of no autocorrelation; ARCH-LM (Lagrange multiplier) tests the null hypothesis of conditional homoscedasticity. All three test statistics follow a χ^2-distribution with degrees of freedom equal to number of lags. At the 5% level, the critical values of all tests for 12 and 24 lags are 21.03 and 36.42.

5 Estimation results

In this section we investigate the interdependence among stock market returns, interest rates, and exchange rates in Indonesia and Thailand using the DCC approach outlined in the Section 3. We focus on the interrelationship across financial markets within each country and within financial markets across countries. The parameters of the DCC model are estimated in a two-step procedure. We first apply the GARCH(1,1)—with an AR(2) filter to remove serial correlation—and use the filtered series in estimating the DCC model. Using the standardised residuals from the first step we continue with the second step of the estimation of the DCC model. This estimation procedure also produces the dynamic conditional correlations. The estimation results as well as a brief introduction to DCC models are presented in Appendix A.

The filtered series from the first step are shown in Figure 2. All series show an increase in volatility in the middle of 1997. In fact, the Asian crisis began in Thailand in the late spring of 1997 with sustained speculative attacks on the local currency, and continued with its flotation in early July 1997. Within days speculators attacked the Indonesian and the other Asian currencies. This spillover results from financial market interdependencies

Figure 2: Filtered foreign exchange rates, stock market returns, and interest rates; March 3, 1995–December 31, 2001



Note: Financial markets series are filtered using the GARCH(1,1) model with an AR(2) filter.

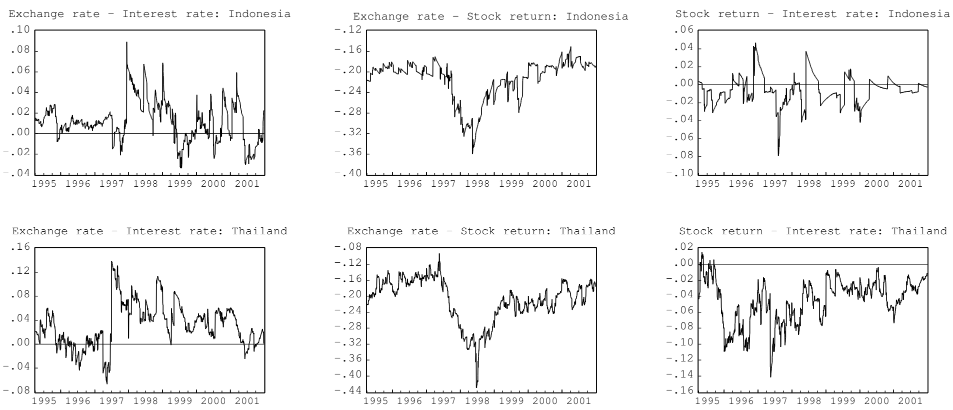
that have been cited as contributing in important ways to the spread of the Asian crisis (see Masson, 1999).

6 Discussion

Figures 3 and 4 plots the dynamic conditional correlations across financial markets within each country and within financial markets across countries, respectively. The conditional correlation patterns shown in these figures reflect the agent's behaviour in the financial markets depending on the state of the economy.

The two graphs in the first column of Figure 3 show the dynamic correlations between exchange rates and interest rates. Prior to a financial crisis, domestic interest rates and the local currency value of the dollar are more likely to be positively than negatively correlated. This may be due to the fact that Indonesia and Thailand pursued a major liberalisation in both the financial and the external sector during the 1980s. As a result, the countries

Figure 3: Dynamic conditional correlations within countries and across financial markets



experienced a surge of capital inflows which led to exchange rate appreciation and declining interest rates. The positive relationship suggests that raising the domestic interest rate does not make the fixed rate regime survive longer than it would without the rate increase. In other words, this may reflect the perverse effects of monetary policy discussed in Section 2 above. The positive correlations between exchange rates and interest rates in Thailand around mid-1997 were quite high. Indonesia experienced high positive correlations in late 1997. These positive correlations indicate that the authorities were not able to fend off the pressures on the currency through spot and forward exchange market interventions and a rise in interest rates. Note also that the pattern of the correlation between interest rates and exchange rates appears to change with the exchange rate regime. This is most clearly seen in Indonesia where the correlation became more volatile with a relatively more flexible exchange rate regime during and after the crisis.

The correlation of the stock market return and the exchange rate in Indonesia and Thailand is negative throughout the sample period (see the middle panel of Figure 3). The negative relationship became stronger during the financial crisis and reached peak levels in 1998 at the height of the Asian crisis. The heavy losses on stock markets during the crisis reflect the effects of the currency depreciation and higher domestic interest rates on highly

Figure 4: Dynamic conditional correlations within financial markets and across countries

leveraged corporate and financial sector balance sheets (see International Monetary Fund, 1998; Goldstein, 1998; Furman and Stiglitz, 1998). Private investor's expectations on the economic situation and policy actions played a role in the stock market crash. Since the Thai baht came under downward pressure in 1996—followed by the Indonesian rupiah in mid-1997 due to speculative attacks—the main immediate concern was to sustain ability the exchange rate peg in the face of a large current account deficit, high short-term foreign debt, the collapse of a property price bubble, and an erosion of external competitiveness. As on previous occasions, the authorities tried to tackle the pressure by pursuing a strategy to intervene on the exchange market by selling international reserves at the pegged rate and by temporarily raising the interest rates. Although this strategy may have worked for some time, the measures taken were seen by markets to be inadequate, perhaps particularly in their lack to address the weaknesses in the financial sector and also because confidence was lost in the ability of the central bank to maintain the peg much longer. Consequently, depositors in domestic banks closed their accounts, and expectations of bank failures built up; investors in the stock market rushed to sell their holdings, causing stock prices to plunge and international lenders refused to roll over maturing loans.

The two graphs at the right-hand-side of Figure 3 show the relationship between stock market returns and interest rates. The negative correlation between the financial markets in Thailand almost dominates the whole sample and reaches its highest negative value in mid-1997. Meanwhile, the correlation sign switches over time in Indonesia, but it is clearly negative during the crisis episode. The behaviour of the dynamic relationship between these markets is much more reflected by the linkages of markets discussed above, i.e. between the foreign exchange and money market, and the stock market against foreign exchange market.

The correlations across countries in a single financial market are shown in Figure 4. At the start of the crisis the correlations drop sharply which implies that the financial markets become less synchronised. This indicates that contagion across the border is not immediate but takes some time. This is due to the fact that in the two crisis countries speculative attacks and corporate and financial problems are clearly reflected by depreciating exchange rates and declining stock prices. In Thailand episodes of speculative attacks and the sharp slide of stock prices began in early 1996. In Indonesia the value of local currency and stock prices did not drop until the Thai currency crisis peaked in mid-1997. For all correlations there is a clear change in the correlation structure starting with the crisis. An abrupt jump in the correlations is noticeable during the crisis period. In the case of interest rate relationship the correlation turns out to be negative at the outbreak of the crisis in mid-1997. This indicates that Thai authorities first reacted by raising the interest rate to defend the currency. Only after the crisis intensified, Indonesia followed with the same response. This confirms the importance of the role of policy makers in influencing outcomes and postponing the effects of a crisis until some later date. Overall, the regional correlations of exchange rates as well as that of stock prices are positive which implies a certain degree of interdependence. In contrast, the co-movement of short-term interest rates is generally much lower.

7 Conclusion

This paper examined inter-financial market linkages and cross-border linkages in the emerging markets of Indonesia and Thailand. Using daily data on short-term interest rates (which capture monetary policy), exchange rates and stock market returns for the period March 3, 1995 through December 31, 2001, we estimated a multivariate GARCH model with a dynamic conditional correlation specification to investigate the issue. DCC parameters and time-varying correlations provided evidence for the inter-financial markets linkage in each country and the cross-border relationship within financial markets.

The outcomes indicate that the relationship among financial markets changed over time and intensified during the Asian financial crisis. Evidence suggests that the linkages between financial markets is significantly affected by the crisis events. Also the way policy makers and the private sector reacted is affected by the financial crisis. In particular, we find positive correlations between exchange rates and interest rates in mid-1997 in Thailand and in late 1997 in Indonesia. This result indicates that excessive tight monetary policy led to a nominal exchange rate appreciation. In contrast, throughout the sample the correlation between the stock market return and the exchange rate is negative. The relationship between stock market returns and interest rates in Thailand was negative for almost the whole sample, but the sign of the correlation changed over time in Indonesia. Financial markets across the countries responded well to each other. In particular, the correlations reveal a certain degree of interdependence between countries, which are lower especially during the crisis episodes.

A The DCC model

The DCC model assumes that the returns from k assets, r_t, are conditionally multivariate normally distributed with zero expected value and covariance matrix H_t.

$$r_t|\Phi_{t-1} \sim N(0, H_t), \tag{A.1}$$

$$H_t \equiv D_t R_t D_t, \tag{A.2}$$

where r_t is a $k \times 1$ vector; H_t is the conditional covariance matrix; R_t is the $k \times k$ time-varying correlation matrix; and all available information up to $t - 1$ is contained in Φ_{t-1}. The returns can be either random error processes (mean zero) or residuals from a filtered time series. D_t is the $k \times k$ diagonal matrix of time-varying standard deviations from univariate GARCH models with $\sqrt{h_{it}}$ as the i^{th} element of the diagonal. D_t is obtained from the following univariate GARCH specification

$$h_{it} = \omega_i + \sum_{p=1}^{P_i} \alpha_{ip} r_{it-p}^2 + \sum_{q=1}^{Q_i} \beta_{iq} h_{it-q},$$

where ω_i is the constant value; for i = 1, 2,...,k with the usual GARCH restrictions for non-negativity and stationarity of the variances, i.e., non-negativity of the parameters and $\sum_{p=1}^{P_i} \alpha_{ip} + \sum_{q=1}^{Q_i} \beta_{iq} < 1$. If these conditions are satisfied, H_t will be positive definite for all t.

Dividing each return by its conditional standard deviation, $\sqrt{h_{it}}$, one obtains the vector of standardised returns, $\epsilon_t = D_t^{-1} r_t$ where $\epsilon_t \sim N(0, R_t)$. This vector may be used to write Engle's (2002) specification of a dynamic correlation structure for the set of returns

$$Q_t = (1 - \sum_{m=1}^{M} \alpha_m - \sum_{n=1}^{N} \beta_n)\bar{Q} + \sum_{m=1}^{M} \alpha_m (\varepsilon_{t-m} \varepsilon_{t-m}^{'}) + \sum_{n=1}^{N} \beta_n Q_{t-n}, \tag{A.3}$$

$$R_t = {Q_t^*}^{-1} Q_t {Q_t^*}^{-1},$$

where $\bar{Q}$ is the unconditional covariance of the standardised residuals resulting from the first stage estimation and Q_t^* is a diagonal matrix composed of the square root of the diagonal elements of Q_t. The elements of R_t will be of the form $\rho_{ijt} = q_{ijt}/\sqrt{q_{iit} q_{jjt}}$, where q_{ijt}, q_{iit}, and q_{jjt} are the elements of Q_t corresponding to the indices. For R_t to be positive definite the only condition that needs to be satisfied is that Q_t is positive definite. See Engle and Sheppard (2001) for details on the condition of R_t. Equation (A.3) is referred to as a DCC(m,n) model.

Engle (2002) shows that under the normality assumption of Equation (A.1), the log-likelihood function for the estimation of Equation (A.3) is given by

$$L = -\frac{1}{2}\sum_{t=1}^{T}\Big(k\log(2\pi) + \log(|H_t|) + r_t^{'}H_t^{-1}r_t\Big). \qquad \text{(A.4)}$$

Substituting Equation (A.2) into Equation (A.4) and using $\epsilon_t = D_t^{-1}r_t$, the simplified log-likelihood function is given by

$$L = -\frac{1}{2}\sum_{t=1}^{T}\Big(k\log(2\pi) + 2\log(|D_t|) + \log(|R_t|) + \varepsilon_t^{'}R_t^{-1}\varepsilon_t\Big). \qquad \text{(A.5)}$$

The formulation of the log-likelihood function in Equation (A.5) allows the model to be easily estimated by separating the estimation procedure in a volatility part and a correlation part. The resulting estimates will be consistent but inefficient. The first stage of the estimation process replaces R_t with the $k \times k$ identity matrix to get the first stage likelihood. This reduces Equation (A.5) to the sum of the log-likelihoods of univariate GARCH equations. The second stage estimates the DCC parameters in Equation (A.3) using the original likelihood in Equation (A.5) conditional on the first stage univariate parameter estimates. The parameter estimates of the two stage DCC estimator are consistent and asymptotic normal. See Engle and Sheppard (2001) and White (1996) for detailed proofs.

Table A.1 presents the estimation results of the univariate GARCH(1,1) model with an AR(2) filter and the DCC(1,1) model using daily data for stock market returns, interest rates, and exchange rates for Indonesia and Thailand for the period March 3, 1995–December 31, 2001. It shows that most of the univariate GARCH parameters are significant. DCC parameter estimates are also significantly different from zero. In all models $\alpha + \beta < 1$, and very close to one. This implies that the volatility process is stable and shows a high degree of persistence. Table A.2 shows that the volatility models are adequate: the standardised squared residuals are serially uncorrelated and there is no autoregressive conditional heteroscedasticity up to order 24 in the standardised residuals.

Table A.1: Estimation results of the GARCH(1,1) model with an AR(2) filter and the DCC(1,1) model, t-values are given between brackets

	AR(2) Parameters (t-values)			GARCH(1,1) Parameters (t-values)		
	φ_0	φ_1	φ_2	ω	α	β
Exchange rates						
Indonesia	−13.46	1.09	−0.09	2.26	0.18	0.81
	(−28.39)	(63.36)	(−4.92)	(28.02)	(42.15)	(12.96)
Thailand	0.01	0.98	0.02	3.91×10^{-5}	0.13	0.86
	(1.48)	(42.65)	(1.89)	(11.14)	(28.86)	(22.09)
Stock market returns						
Indonesia	0.02	0.83	0.16	2.61	0.08	0.90
	(9.26)	(43.21)	(8.18)	(6.27)	(27.71)	(72.43)
Thailand	0.00	1.12	−0.12	4.87×10^{-5}	0.05	0.94
	(1.68)	(50.79)	(−5.44)	(2.81)	(13.00)	(51.09)
Interest rates						
Indonesia	−0.11	0.75	0.26	0.00	0.11	0.88
	(−6.23)	(43.51)	(14.97)	(9.33)	(61.65)	(81.63)
Thailand	0.04	1.06	−0.07	0.02	0.18	0.80
	(2.00)	(58.01)	(−4.03)	(38.29)	(29.81)	(93.95)
DCC(1,1)						
Parameters					0.01	0.97
t-values					(6.07)	(38.41)

Note: The AR(2) filter takes the form $r_t = \varphi_0 + \varphi_1 r_{t-1} + \varphi_2 r_{t-2} + u_t$.

Table A.2: Testing serial correlation and ARCH effects of filtered series of foreign exchange rates, stock market returns, and interest rates; March 3, 1995–December 31, 2001

	Ljung-Box Q-statistics residuals		Ljung-Box Q-statistics squared residuals		ARCH-LM residuals	
	12 lags	24 lags	12 lags	24 lags	12 lags	24 lags
Exchange rates						
Indonesia	20.13	36.33	11.96	19.29	6.24	11.66
Thailand	13.64	28.79	9.57	12.78	8.96	13.05
Stock market returns						
Indonesia	20.40	34.51	16.91	20.39	16.57	20.05
Thailand	20.76	32.70	15.23	34.05	23.13	34.50
Interest rates						
Indonesia	14.12	29.42	12.76	15.69	17.58	21.36
Thailand	20.77	28.18	0.97	1.98	0.69	1.51

Note: The diagnostics are computed for the standardised residuals. The Ljung-Box Q-statistic tests the null hypothesis of no autocorrelation; the ARCH-LM (Lagrange multiplier) tests the null hypothesis of conditional homoscedasticity. Both test statistics follow a χ^2-distribution with degrees of freedom equal to the number of lags. At the 5% level, the critical values of all tests for 12 and 24 lags are 21.03 and 36.42, respectively.

References

Aghion, P., P. Bacchetta, and A. Banerjee (2001), "Currency crises and monetary policy in an economy with credit constraints", *European Economic Review*, **45**(7), 1121–1150.

Alexander, C. (2002), "Principal component models for generating large GARCH covariance matrices", *Economic Notes*, **31**(2), 337–359.

Bautista, C.C. (2003), "Interest rate-exchange rate dynamics in the Philippines: a DCC analysis", *Applied Economics Letters*, **10**(2), 107–111.

Bera, A.K. and M.L. Higgins (1993), "ARCH models: properties, estimation and testing", *Journal of Economic Surveys*, **7**(4), 305–366.

Bollerslev, T. (1990), "Modelling the coherence in short-run nominal exchange rates: A multivariate generalized ARCH model", *Review of Economics and Statistics*, **72**(3), 498–505.

Bollerslev, T., R.Y. Chou, and K.F. Kroner (1992), "ARCH modeling in finance: a review of the theory and empirical evidence", *Journal of Econometrics*, **52**(1-2), 5–59.

Bollerslev, T., R.F. Engle, and D. Nelson (1994), "ARCH models", in R. Engle and D. McFadden, editors, *Handbook of Econometrics*, North Holand, Amsterdam, 2959–3038.

Bollerslev, T., R.F. Engle, and J.M. Wooldridge (1988), "A capital asset pricing model with time-varying covariances", *Journal of Political Economy*, **96**(1), 116–131.

Chowdhry, B. and A. Goyal (2000), "Understanding the financial crisis in Asia", *Pacific-Basin Finance Journal*, **8**(2), 135–152.

Corsetti, G., P. Pesenti, and N. Roubini (1999), "What caused the Asian currency and financial crisis?", *Japan and the World Economy*, **11**(3), 305–373.

Dornbusch, R. and S. Fischer (1980), "Exchange rates and the current account", *American Economic Review*, **70**(5), 960–971.

Dungey, M., R. Fry, B. González-Hermosilo, and V.L. Martin (2005), "A comparison of alternative tests of contagion with applications", in M. Dungey and D.N. Tambakis, editors, *Identifying International Financial Contagion: progress and challenges*, Oxford University Press, New York, 60–85.

Elyasiani, E. (2004), “Interest rates, risk, and imperfect markets: puzzles and policies”, *Oxford Review of Economic Policy*, **15**(2), 59–76.

Engle, R.F. (1982), “Autoregressive conditional heteroscedasticity with estimates of the variance of United Kingdom inflation”, *Econometrica*, **3**(1), 987–1008.

Engle, R.F. (2002), “Dynamic conditional correlation: A simple class of multivariate generalized autoregressive conditional heteroskedasticity models”, *Journal of Business and Economic Statistics*, **20**(2), 339–350.

Engle, R.F. and K. Kroner (1995), “Multivariate simultaneous GARCH”, *Econometric Theory*, **11**(1), 122–150.

Engle, R.F., V.K. Ng, and M. Rothschild (1990), “Asset pricing with a factor-ARCH covariance structure : Empirical estimates for treasury bills”, *Journal of Econometrics*, **45**(1-2), 213–237.

Engle, R.F. and K. Sheppard (2001), “Theoretical and empirical properties of dynamic conditional correlation multivariate GARCH”, *NBER Working Paper* 8554, National Bureau of Economic Research, Cambridge, MA.

Franses, P. and Van Dijk, D. (2000), *Non-linear Time Series Models in Empirical Finance*, Cambridge University Press, UK.

Furmans, J. and J.E. Stiglitz (1998), “Economic crises: evidence and insights from East Asia (with comments and discussion)”, *Brookings Papers on Economic Activity*, **2**, 1–135.

Gavin, M. (1989), “The stock market and exchange rate dynamics”, *Journal of International Money and Finance*, **8**(2), 181–200.

Goldstein, M. (1998), *The Asian financial crisis: causes, cures, and systemic implications*, Institute for International Economics, Washington, D.C.

Gourierroux, C. and J. Jasiak (2001), *Financial Econometrics*, Princeton University Press, New Jersey.

Hekman, C.R. (1985), “A financial model of foreign exchange exposure”, *Journal of International Business Studies*, **16**(2), 83–99.

International Monetary Fund (1998), *IMF World Economic Outlook*, World Economic and Financial Surveys, International Monetary Fund, Washington, D.C.

Koutmos, G. and A.D. Martin (2003), "Asymmetric exchange rate exposure: theory and evidence", *Journal of International Money and Finance*, **22**(3), 365–383.

Longin, F. and B. Solnik (1995), "Is the correlation in international equity returns constant: 1960-1990?", *Journal of International Money and Finance*, **14**(1), 3–26.

Markowitz, H.M. (1952), "Portfolio selection", *Journal of Finance*, **7**(1), 77–91.

Masson, P. (1999a), "Contagion: monsoonal effects, spillovers, and jumps between multiple equilibria", in P.R. Agénor, M. Miller, D. Vines, and A. Weber, editors, *The Asian Financial Crisis: Causes, Contagion and Consequences*, Cambridge University Press, Cambridge, UK, 265–283.

Pagan, A. (1996), "The econometrics of financial markets", *Journal of Empirical Finance*, **3**(1), 15–102.

Radelet, S. and J.D. Sachs (1998), "The East Asian financial crisis: diagnosis, remedies, prospects (with comments and discussion)", *Brookings Papers on Economic Activity*, **1**, 1–74.

Sercu, P. and C. Vanhulle (1992), "Exchange rate volatility, international trade and the value of exporting firms", *Journal of Banking and Finance*, **16**(1), 155–182.

Tse, Y. (2000), "A test for constant correlations in a multivariate GARCH model", *Journal of Econometrics*, **98**(1), 107–127.

Tse, Y. and A. Tsui (2002), "A multivariate generalized autoregressive conditional heteroscedasticity model with time-varying correlations", *Journal of Business and Economic Statistics*, **20**(3), 351–362.

White, H. (1996), *Estimation, Inference and Specification Analysis*, Cambridge University Press, UK.

Yang, S.Y. (2005), "A DCC analysis of international stock market correlations: the role of Japan on the Asian four tigers", *Applied Financial Economics Letters*, **1**(2), 89–93.

Zapatero, F. (1995), "Equilibrium asset prices and exchange rates", *Journal of Economic Dynamics and Control*, **19**(4), 787–811.