Volatility transmissions between renminbi and Asia-Pacific on-shore and off-shore U.S. dollar futures

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ABSTRACT

This paper uses multivariate GARCH techniques to study volatility spillovers between the Chinese non-deliverable forward market and seven of its Asia-Pacific counterparts over the period January 1998 to March 2005. To account for the time-variability of conditional correlation, a dynamic correlation structure is included in the volatility model specification. The empirical results demonstrate that the renminbi non-deliverable forward (NDF) has been a driver of various Asian currency markets but that such co-movements exhibit a substantial degree of heterogeneity. As to the determinants of the magnitude of these co-movements, we test the relevance of potential factors and find that it is the degree of real and financial integration, in particular, that exerts the largest influence on volatility transmission.

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1. Introduction

The financial turmoil in the Asia-Pacific region in the 1990s has sparked intense interest in the degree of international financial integration and in co-movements between foreign exchange markets. The removal of capital controls in emerging markets and the subsequent vast capital inflows seeking higher returns in these developing economies provide ample proof that financial markets became increasingly integrated during the recent decade. In tandem with these financial developments, a seemingly unstoppable Chinese export drive has redrawn the lines of international trade.1 Following more than two decades of market-oriented reforms, China has become an international production hub which combines a vast supply of cheap labour with an economy that is unusually open by international standards. The sum of exports and imports amounted to about 75 percent of China’s GDP in 2004, compared to around 25–30 percent in Brazil and India. Thus China has an impact upon the world economy that amounts to a substantial supply shock. This has raised the world’s potential GDP growth rate, helped to hold down inflation, and triggered significant changes in relative prices of labour, capital, and goods. Furthermore, China as a potential market far exceeds Europe, and it is hard to dispute that China has the potential to be a principal engine of world economic growth in the twenty-first century. World trade patterns and production structures in the rest of the world will have to adjust to accommodate China’s emergence as a global economic player.

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1 See Rodrik (2006) for a comprehensive analysis of China’s export success.

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Since China is especially open to trade, it is not merely a driver of global growth, but also has a highly pervasive impact on other economies. Whereas ten years ago a downturn in the Chinese economy may not have had far-reaching repercussions for the rest of the world, today the consequences of such would be far more perilous for global economic growth. In light of this, the Chinese currency regime has become one of the most intensely debated issues in international economics.

On July 21, 2005, after more than a decade of pegging the renminbi (RMB) to the U.S. dollar (USD) at an exchange rate of 8.28, the People’s Bank of China (PBOC) announced a revaluation of the currency, together with a reform of the exchange rate regime. Under the reform, the PBOC manages the renminbi against an undisclosed basket of currencies of China’s main trading partners. The initial revaluation put the renminbi at 8.11 against the dollar, which amounts to an appreciation of 2.1 percent. Although critics were not impressed with the initial appreciation of the RMB, much initial excitement surrounded the Chinese pledge to link the RMB to a group of major currencies. Many economists have argued that the modest RMB revaluation merely marks the beginning of a more significant evolution of the currency regime which could translate into a major upward revaluation of the RMB in accordance with market forces.

The Chinese basket peg replaces the obligation to hold the RMB exchange rate within a fixed margin of the USD with an obligation to hold the RMB within a fixed margin of a constant nominal value of a basket of currencies. On 10 August 2005, three weeks after China abandoned its decade-old peg to the USD, the PBOC revealed the mix of this basket. However, the weights attached to each currency were not revealed. According to the PBoC, the USD, the Japanese yen, the euro and the South Korean won have the largest weights, but the basket also includes the currencies of Australia, Canada, Great Britain, Malaysia, Russia, Singapore, and Thailand. Given the political problems this might pose, the Hong Kong and Taiwanese dollars are absent. The choice of currencies (and hence presumably the weights), depends not only on the pattern of China’s trade but also on the sources of its foreign direct investment and the currency composition of its reserves.

The operation of the new system involves the daily calculation of a new central parity ("medium value" in the gap/band). Initially the trading range was monitored and controlled at ±0.15% around this medium value for the USD, with different ranges for other currencies (perhaps 0.5–1% for the euro and the Japanese Yen). On 18 May 2007, the PBoC eventually widened the RMB’s daily trading band against the USD from 0.30% to 0.50%.

Despite this policy change, many economists argue that the present situation still does not represent an equilibrium and that the current renminbi revaluation merely marks the beginning of a more significant evolution of the currency regime. Greater flexibility in China’s exchange rate is viewed as an essential element of a global response to the large macroeconomic imbalances in the world economy. The United States has been joined by the international community, including the G-7, IMF, and Asian Development Bank, in vigorously encouraging China to implement greater exchange rate flexibility, which would be associated with a larger renminbi appreciation.

Arisng of this, the Chinese currency’s future path, as well as in co-movements across Asian currencies, continues to demand the attention of policymakers and academics alike. This stems from the fact that, while China’s Asian trading partners are becoming of growing importance in the world economy, today the consequences of such would be far more perilous for global economic growth. In light of this, the Chinese currency regime has become one of the most intensely debated issues in international economics.2

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Arisng of this, the Chinese currency’s future path, as well as in co-movements across Asian currencies, continues to demand the attention of policymakers and academics alike. This stems from the fact that, while China’s Asian trading partners are weighted significantly in its trade-weighted index, China is also an important trade partner for them. As a consequence, PBOC’s exchange rate policy is likely to influence the path of many Asian currencies. Indeed, McKinnon (2005) has recently argued that a number of China’s main Asian trading partners have smoothed their dollar exchange rates in an effort to retain competitiveness against China.

Despite the great interest in the topic, no papers have addressed the issue of interdependence among Asian exchange rate markets via temporal volatility (or conditional variances) so far. The lack of research dedicated to this is quite surprising.6 The objective of this study is twofold. We first scrutinize the nature of co-movements between Chinese and other Asian forward exchange rates in order to shed some light on how, and to what extent, the volatility of Asian currencies is affected by renminbi exchange rate developments. We then explore whether the interaction between China and other Asia-Pacific countries has changed since the 1997–98 crisis. To state it more intuitively, this paper aims to provide answers to questions such as: where are volatilities spillovers between Chinese and other Asian forward exchange rates? Have the correlations between those markets changed over time, and in particular after the Asian crisis and the PBoC policy change in 2005? Which are the potential...

2 The terms “renminbi” and “yuan” are generally used interchangeably to refer to China’s currency. The renminbi is the currency, while the yuan is the unit of account.

3 This poses a problem in that the announcement and subsequent clarifications leave the Chinese central bank with considerable discretion over its renminbi target. The obvious disadvantage of the undisclosed basket peg therefore is a lack of transparency. Markets may become frustrated about what may happen next.

4 There are several similarities between the Chinese system and Singapore’s basket system. Singapore adopted its basket approach in 1981 and it was seen as a halfway house between fixed and flexible currencies. Notable similarities between the two systems include the following: (i) both countries link their currency to a basket of major currencies; (ii) both have a central parity and a moving band; and finally (iii) Singapore does not reveal exactly how its basket of currencies is constructed, an approach China appears to be emulating. The motivation is to ward off speculators. On the other hand, there is no capital control in Singapore and therefore no need to publish the official central parity. The band for Singapore is announced semi-annually. Singapore’s Monetary Authority intervene at their own discretion to maintain the central parity and the band. The PBOC publishes the central parity every evening (necessitated by the fact that they have capital control and RMB is not freely tradable).

5 Funke and Rahn (2005) have estimated that the renminbi exchange rate against the U.S. dollar is undervalued by 10-15 percent compared to the equilibrium rate. A survey of equilibrium exchange rate estimates for China is provided by Li and Dunaway (2005) and Dunaway et al. (2006).

6 Co-movements between markets occur as rational agents try to infer information from price changes in other markets. A number of papers have demonstrated that the nature of such financial market linkages is time-varying [see Beko and Harvey (1995, 1997)]. Park (2001) is the sole paper to date analysing interrelations and information flows across non-deliverable forward and spot markets for the Korean won.
The reminder of the paper is organized as follows. Section 2 outlines the characteristics of the Asian Non-Deliverable Forward (NDF) market, as well as describing the dataset used in this study. Section 3 discusses the methodology employed and presents the bivariate GARCH models used to model volatility spillovers, together with the dynamic correlation structure. Section 4 analyses the empirical results and Section 5 investigates a variety of potential determinants of the magnitude of co-movements across countries. Section 6 summarizes the findings and concludes with some general remarks.

2. Data description

The aim of this section is twofold. We first present the dataset used in our study, highlighting the main features of markets for NDF in Asian currencies. We then present a set of scatter plots for the analysed variables in order to provide some preliminary evidence for volatility clustering in the data.

The evolution of forward exchange rate markets, which are considered a gauge of the anticipated direction of a change of a currency’s value, is closely monitored by a diverse range of economic agents. However, a number of emerging market economies restrict the access of foreign firms and international investors to on-shore financial markets and, as a consequence, forward markets either do not exist or are underdeveloped. Since the early 1990s, however, some international banks have been providing an offshore, over-the-counter, market in NDFs for many emerging-market currencies, one of which includes the Chinese RMB.

In order to analyse of co-movements in Chinese and Asian forward exchange rates, we use daily observations of forward exchange rates for eight Asian countries. These eight countries can be classified as (1) Greater China (China and Hong Kong), (2) the NIE’s (Korea, Singapore and Taiwan), and (3) three ASEAN countries (Indonesia, Malaysia, Philippines). Our dataset includes on-shore and off-shore forward exchange rates with maturities of 1 month to 12 months. Generally, contracts longer than 12 months were not readily available. As the NDF markets only began full scale trading in 1996–97, our sample commences in 1998 and spans the period 1 January 1998 to 31 December 2007. The country coverage is detailed in Table 1.

As is the case with standard forward contracts, NDF exchange rates for conversion are fixed for a future date. Thus, the NDF contract is similar to a regular forward foreign exchange contract, except that at maturity the NDF is settled in another currency, typically the USD, because the domestic currency is subject to capital controls, and is therefore “non-deliverable”. Effectively, the NDF user is financially protected from exchange rate fluctuations by the compensating USD payment paid or received, based on the NDF fixed rate. In contrast to standard deliverable forwards, Asian NDFs are traded over the counter (OTC) and offshore, i.e. outside the jurisdiction of the authorities of the corresponding currency. Trading predominantly takes place in Hong Kong and Singapore and, to a lesser extent, London and Tokyo.

Active and growing NDF markets exist for several Asian currencies. These offshore markets offer international investors an otherwise unavailable hedging tool against local currency exposure. An analysis of Asian NDF markets as a whole, together with a discussion of the basic institutional features of the renminbi NDF market, is provided by Fung et al. (2004), Ma, Ho and McCauley (2004) and Debelle, Gytentberg and Plumb (2006). Ma et al. (2004) and Debelle et al. (2006) discuss the deepening of the Asian NDF markets in recent years. Turnover has been highest on the Korean won, Taiwan dollar, and Chinese RMB markets, though the remaining, shallower markets have also deepened in recent years. RMB NDFs with the

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Notes: The table shows the data availability for all countries in the sample. √ indicates data availability. All daily data are currency option quotes in Hong Kong, the observations being recorded at the close of business.

<table>
<thead>
<tr>
<th>Country</th>
<th>Local currency</th>
<th>On-shore forward contracts</th>
<th>Off-shore forward contracts</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Renminbi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Hong Kong Dollar</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>Rupiah</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Malaysia</td>
<td>Ringgit</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Philippines</td>
<td>Peso</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Singapore</td>
<td>Singapore Dollar</td>
<td>√</td>
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<tr>
<td>South Korea</td>
<td>Won</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Taiwan</td>
<td>Taiwan Dollar</td>
<td></td>
<td>√</td>
</tr>
</tbody>
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Ma and McCauley (2008) have shown that China’s capital controls remain substantially binding. Although the Chinese capital controls have not been watertight, they find sustained and significant gaps between onshore and offshore renminbi interest rates and persistent RMB/USD interest rate differentials during the de facto dollar peg period.

Onshore banks in countries with capital controls can sometimes gain indirect access to NDF markets via offshore subsidiaries, such as a subsidiary of a Chinese bank located in Hong Kong.
USD, for example, have a daily trading volume ranging from approximately US$150 million to US$700 million, with increasing participation from international hedge funds. This suggests that the level of market liquidity is sufficient for fluctuations in NDF prices to serve as a meaningful indicator of the market’s belief about the future path of the renminbi against the USD. A NDF is a zero-sum game in which setting the NDF contract’s exchange rate equal to the expected future spot rate minimizes one participant’s loss (and the other’s gain). Hence, the parties will use all available information in forming their expectations and therefore prices in the NDF market can be a useful informational tool to gauge market expectations of potential pressures on an exchange rate regime going forward. The one-, three-, and twelve-month RMB NDF exchange rates are plotted in Fig. 1.

Given that it is centered on the pre-reform peg of 8.28 renminbi per dollar, the chart indicates that prior to mid-2002 the NDF market expected a depreciation of the renminbi (NDF rates were constantly higher than the target rate), which never materialized. Since late 2002 or early 2003, the NDF market has consistently expected – and missed – an appreciation of the Chinese currency relative to the USD. At 21 July, 2005, the day of the regime change, three-month NDF rates dropped below 8 RMB per dollar, anticipating further appreciation of the RMB-USD exchange rate. At 31 December 2007, the market seems to expect that the renminbi will appreciate an additional 8.5 percent over the next year, but such a precise reading of these data is premature because it fails to account for the pricing implications of risk.

In our study we analyse the continuously compounded daily returns on one-year NDFs of the forementioned eight Asian countries. All the series appear to have fat-tailed distributions relative to the normal distribution, with significant linear and non-linear serial correlations. With respect to non-linear serial correlations, it is often observed that large changes tend to be followed by large changes, and small changes tend to follow small changes. This regularity, known as volatility clustering, is even more evident in high-frequency financial data and our dataset is no exception. The daily returns on one-year NDF contracts for our set of countries are plotted in Fig. 2: the existence of volatility clustering is clearly evident.

To shed further light on the extent of linkages among Asian forward exchange rate markets, Fig. 3 displays a set of scatter diagrams, each plotting the Chinese return series on the vertical axis and the return series of one of the remaining Asian countries on the horizontal axis together with a regression fit line. As one would expect, the diagrams highlight the fact that the observations for all country pairs are concentrated near a line of positive slope and falling in the symmetric quadrants (+,+), and (−,−), indicating a tendency to have unusually large values of the two series simultaneously. In particular, this evidence implies that the information revealed in one market is factored into the behavior of other market.

The key insight to emerge from this analysis is that clear links can be observed between daily returns on one-year NDF contracts between China and its Asian counterparts. This link manifests itself most visibly in the cases of Korea, Taiwan, and Philippines, as it is these countries that appear to exhibit the strongest interdependence with China. Given this preliminary data analysis, it is now

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9 The PBOC has announced that it will allow more domestic banks to participate in its forward exchange market. The goal is to develop on-shore markets in which firms can hedge their foreign exchange exposures. Eventually, it is envisaged that such markets will supplant the NDF market. In this way, NDF markets can be seen as an intermediate step in the process of market integration from limited to full capital convertibility. See http://www.pbc.gov.cn/english/detail.asp?col=6800&id=50. An important question then is how to facilitate the transition from offshore NDF markets to regular onshore forward markets. De belle et al. (2006) have drawn lessons from the previous Australian transition from an NDF market to a deliverable forward market following the float of the Australian dollar.

10 Even when a substantial revaluation of the renminbi is not the most likely prediction for the foreseeable future, the market price will nevertheless include compensation for the small probability of a substantial renminbi appreciation. This risk premium for the small probability of a large adjustment, i.e. the so-called peso problem, causes the NDF rate to deviate on one side of the pegged exchange rate since the beginning of 2003.

11 The forward rate reflects exchange rate risk, and incorporates both expectations about the expected future spot rate and a currency risk premium.

12 This may be called the Chinese dominance hypothesis, by which financial markets perceive different exchange rates to be the same, and therefore a new piece of information arriving to the market causes them to move in the same direction.

13 The linkages between markets are an important element from the point of view of investors, as these estimates provide the necessary inputs for models used to construct efficient hedging and diversification portfolio strategies.

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pertinent to undertake an assessment of volatility spillovers across Asian countries. The methodology of this step is that of a multivariate GARCH model.

3. Multivariate GARCH framework

A topic at the forefront of the research agenda in financial econometrics is the construction and analysis of models capable of summarising the volatility properties of two or more asset returns. A striking empirical regularity that emerges from numerous empirical studies using high-frequency financial data is the finding of GARCH behavior.\(^\text{14}\) We therefore address the topic of cross-country volatility spillovers in a multivariate GARCH model framework.\(^\text{15}\) In the multivariate GARCH literature one of the most prominent problems is the “curse of dimensionality”, due to the large number of parameters. To make computation more tractable, Bollerslev (1990) and Engle (2002) have suggested the Constant Conditional Correlation (CCC) and its extension, the Dynamic Conditional Correlation (DCC) model which probably is the most popular multivariate GARCH parameterization. Both frameworks combine flexibility and a parsimonious specification with appropriate restrictions ensuring positive definite variance-covariance matrices.

\(^{14}\) A large number of previous papers have documented the persistence of volatility in nominal exchange rates; see, for example, Baillie and Bollerslev (1989), Bollerslev (1987, 1990), Hsieh (1989) and McCurdy and Morgan (1987, 1988).

\(^{15}\) It would be impossible, and it is not our intention here, to provide an overview of the multitude of GARCH models recently developed. See Bauwens, Laurent and Rombouts (2003), Brooks, Burke and Persand (2003), Lütkepohl (2005), pp. 557-584 and Tsay (2005), pp. 443-489 for comprehensive surveys of the multivariate GARCH literature.
Suppose \( r_{i,t} \) and \( r_{CH,t} \) denote the 1-year NDF’s daily return of market \( i \), for \( i = 1, \ldots, N \) and China, respectively, for \( t = 1, \ldots, \text{T} \). \( \sigma_{i,t}^2 \) and \( \sigma_{CH,t}^2 \) represent the conditional variance of market \( i \) and China, respectively, and the conditional covariance between the Asian market \( i \) and China. \( \varepsilon_{i,t} \) and \( \varepsilon_{CH,t} \) are the shocks, or innovations, of NDF market \( i \) and the Chinese market, which, in our case, are assumed to be conditionally \( t \)-distributed. The conditional covariance matrix of \( \varepsilon_t = (\varepsilon_{i,t}, \varepsilon_{CH,t})' \), given the past information, \( \Omega_{t-1} \), is denoted by \( \Omega_t \) and it is defined by \( \Omega_t = \text{Cov}(\varepsilon_t | \Omega_{t-1}) \). Multivariate volatility modelling is concerned with the finding a suitable model for the time evolution of \( \Omega_t \). The general bivariate GARCH model is formulated as follows:

\[
\begin{pmatrix}
    r_{i,t} \\
    r_{CH,t}
\end{pmatrix} = \begin{pmatrix}
    \mu_{i,0} \\
    \mu_{CH,0}
\end{pmatrix} + \begin{pmatrix}
    \varepsilon_{i,t} \\
    \varepsilon_{CH,t}
\end{pmatrix}
\]

\[
\begin{pmatrix}
    \sigma_{i,t}^2 \\
    \sigma_{CH,t}^2
\end{pmatrix} = \begin{pmatrix}
    \alpha_{i0} & \alpha_{iCH} \\
    \alpha_{CHi} & \alpha_{CHCH}
\end{pmatrix} \begin{pmatrix}
    \varepsilon_{i,t-1}^2 \\
    \varepsilon_{CH,t-1}^2
\end{pmatrix} + \begin{pmatrix}
    \beta_{i0} & \beta_{iCH} \\
    \beta_{CHi} & \beta_{CHCH}
\end{pmatrix} \begin{pmatrix}
    \sigma_{i,t-1}^2 \\
    \sigma_{CH,t-1}^2
\end{pmatrix}
\]

Eq. (1) is the conditional mean equation, where each return variable, \( r_t \), is explained simply by a constant term, \( \mu_{0} \). Eq. (2) describes the conditional variance equation. The conditional variance, \( \sigma_t^2 \), is explained by its own past values as well as by the past values of the squared innovations, \( \varepsilon_t^2 \). Parameters \( \beta_{i0} \) (and \( \beta_{CHCH} \) in our bivariate specification) measure the degree of volatility...
The conditional covariance, $\sigma_{CH,t}$, is specified by using firstly the CCC model [Eq. (4)] and secondly the DCC model [Eqs. (4)–(6)]. The CCC model uses the following reparametrization of the conditional covariance matrix, $H_t$:  

$$H_t = D_t R_t$$  

or  

$$\sigma_{CH,t} = \rho_{CH} \sigma_i \sigma_{CH,t}$$  

where, in our bivariate case, $D_t$ is a $2 \times 2$ diagonal matrix with time varying standard deviations, $\sigma_i$, on the diagonal and $R$ is the time invariant correlation matrix, with $\rho_{CH}$ the cross-market correlation coefficient of the standard residuals between market $i$ and China. Moreover,  

$$D_t = \begin{bmatrix} \sigma_{CH,t} & 0 \\ 0 & \sigma_{CH,t} \end{bmatrix}, \quad R_t = \begin{bmatrix} 1 & \rho_{CH} \\ \rho_{CH} & 1 \end{bmatrix}. \tag{4}$$  

In order to overcome the restrictive assumption of constant correlations, we included into the volatility model specification a DCC structure. In the case of the DCC model $H_t$ is decomposed as follows:  

$$H_t = D_t R_t D_t$$  

or  

$$\sigma_{CH,t} = \rho_{CH} \sigma_i \sigma_{CH,t}$$  

where $R_t$ is the time-varying symmetric conditional correlation matrix and the model is given by:  

$$Q_t = S(1 - a - b) + a z_{t-1} z'_{t-1} + b Q_{t-1}$$  

$$R_t = \text{diag} \left( Q_t \right)^{-1/2} Q_t \text{diag} \left( Q_t \right)^{-1/2}.$$  

where $a$ and $b$ are scalar parameters and $z_t$ are the standardised but correlated residuals. That is, the conditional variances of the components of $z_t$ are equal to 1, but the conditional correlations are given by $R_t$, $\text{diag}(Q_t)$ is a diagonal matrix with the same diagonal elements as $Q_t$, $S$ is the unconditional correlation matrix which in the estimation procedure is replaced by the sample correlation matrix of $z_t$. If $a$ and $b$ are zero, one obtains the above CCC model. If they are different from zero, one gets a kind of ARMA structure for all correlations. Note, however, that all correlations follow the same kind of dynamics, since the ARMA parameters are the same for all correlations.\(^{16}\) In this DCC(1,1) model the number of parameters is 8 in the bivariate case.

Estimation of the dynamic correlation models can be carried out using Quasi-Maximum-Likelihood (QML), following the suggestion of Engle (2002) and Bollerslev and Wooldridge (1992). The CCC and DCC frameworks allow one to “break” the log-likelihood into two parts, one part for the parameters determining univariate volatilities and the other for the parameters determining the correlations (two-step estimation technique). The associated asymptotic standard errors calculated from the QML method are consistent and robust to the density function underlying the residuals.

A crucial assumption of the standard CCC and DCC models is that the returns are normally distributed. The normality assumption allows QML to provide feasible and consistent DCC coefficients of conditional correlations. Financial time series, however, rarely support this assumption. QML estimation under misspecification of the (non-Gaussian) conditional distribution, however, may yield inconsistent parameter estimates [Newey and Steigerwald (1997)]. Furthermore, if excess kurtosis is ignored then the probability of extreme events will almost surely be underestimated with possible serious repercussions for risk management activities. The standard way to overcome drawbacks of the normality assumption involves the use of tick (non-normal) distributions to achieve efficiency. A commonly used assumption is the multivariate t-distribution for the errors.\(^{17}\)

The nonlinearity in the arguments of the likelihood function necessitates a numerical maximisation technique. As in all numerical search procedures, it is crucial to obtain good starting values. Since the simplex algorithm is more robust to initial parameter starting values than the Broyden, Fletcher, Goldfarb, Shanno (BFGS) algorithm, we use the simplex algorithm to provide initial parameter estimates for the BFGS algorithm, which in turn provides the final parameter estimates along with the corresponding variance-covariance matrix. We thereby ensure that the algorithm does not get stuck at a local – as opposed to global – optimum.

In the GARCH family of models, exogenous variables can be included. In our modeling exercise we have included a step dummy variable (0 before July 21, 2005, 1 from July 21, 2005 onwards) in the conditional variance equation to account for higher exchange rate volatility after the regime change. The final specification of the lag structure was chosen using likelihood ratio tests and information criteria. Furthermore, Ljung-Box portmanteau tests were performed on standardized residuals and squared residuals. A GARCH(1,1) specification turned out to be appropriate for all bivariate models.\(^{18}\)

\(^{16}\) Engle and Sheppard (2001) have demonstrated that this restriction of an identical ARMA-type structure leads to some bias in case of many financial assets because employing this a priori restriction violates the data. This assumption may be more easily satisfied by a small number of exchange rates, but it becomes increasingly more unlikely in case of many returns. Therefore, we have estimated several bivariate (pairwise) models to allow for country-specific dynamics.\(^{17}\) Bauwens et al. (2003) review various multivariate asymmetric distributions. However, the majority of these distributions are either too complicated to be estimated for GARCH purposes or present undesirable properties such as infinite variances.\(^{18}\) In most cases, the diagnostic tests fail to detect any serious misspecification of models, thus suggesting that there is little unexplained dependence in the data. In particular, the Ljung-Box tests performed on the squared normalised residuals are reduced substantially compared to the values for the raw squared returns, which indicates that the GARCH(1,1) models do a very good job of tracking the strong temporal dependence in the variance. We have also computed the coefficients of skewness and kurtosis on the standardised residuals, which indicate that strong deviations from normality remain. Standard errors are robust for non-normality of residuals.
Fig. 4. Constant (CCC) and Time-Varying (DCC) Conditional Correlation Coefficients. Period: 1/1/1998 to 31/12/2007. Note: Estimated bivariate conditional correlations between Asian on-shore and off-shore markets and China. The horizontal line (above the zero axis) is the correlation coefficient estimated within the CCC framework.
4. Empirical results

Estimation results for the specified models indicate that strong GARCH effects are evident in virtually all of the regressions, with the sum of estimated (statistically significant) coefficients very close to one. This finding is consistent with the literature on high frequency exchange rate dynamics.\(^{19}\) The estimated daily conditional correlations from the bivariate CCC-GARCH and DCC-GARCH models are plotted in Fig. 4.\(^{20}\)

The estimates obtained within the CCC framework show that Hong Kong and Taiwan are the two Asian countries whose forward market returns have the strongest interdependence with China; their conditional correlation coefficients are 0.31 and 0.31, respectively. Malaysia and Indonesia show the lowest conditional correlations: 0.04 and 0.11, respectively.\(^{21}\)

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\(^{19}\) For the sake of brevity, the GARCH estimation results are not presented here, but are available from the authors upon request. Qualitatively similar results arise for maturities of three, six and nine months.

\(^{20}\) Because of the model’s popularity, Tse (2000) has outlined an LM test that evaluates the constant correlation model against the alternative of the DCC dynamic structure. This computationally convenient test examines the restrictions imposed on a model which encompasses the CCC model. We do not pursue the test in our paper because it is based on the normality assumption.

\(^{21}\) The size of the conditional correlations provides credence to the notion that Chinese financial markets remain partially de-linked due to the absence of full currency convertibility.
Further insights can be gained by allowing the correlation matrix to vary over time. As is evident from Fig. 4, in all cases NDF market return correlations exhibit significant variation, ranging between a maximum of 0.8 and a minimum of -0.4, and have a number of spikes. Apart from a handful of negative values, each of the graphs in Fig. 4 displays conditional correlations of the returns with China, which are all positive. Moreover, the observed correlation coefficients display three distinct changes of pattern over the given time span.

At the beginning of the sample period, the correlation coefficients of each of the countries display a sudden drop followed by a sharp increase between January and September 1998. The magnitude of such shifts appeared to be particularly relevant for Hong Kong, Indonesia and Singapore, but this evidence is common to all the countries studied. The Asian crisis, in fact, began in Thailand in the late spring of 1997 with substantial speculative attacks on the local currency, and continued with its floatation in summer 1997. Speculators also attacked the Indonesian and Korean currencies. Thus, there is strong evidence that during periods of stress and high volatility both the magnitude and persistence of comovements increased significantly.22

Evidence of the second pattern change in conditional correlations between all markets and China is found prior to the regime change in July 2005, when the coefficients trended upwards. Despite this, the timing and magnitudes of the increases differ noticeably from country to country. In the case of Hong Kong and Singapore, the rise in correlation with China occurred at the end of 2003, coinciding with appreciation of the Hong Kong dollar in autumn 2003.23 Hong Kong’s correlation coefficient subsequently increased from near 0 to more than 0.4 in March 2005, while the corresponding figure for Singapore rose to approximately 0.3 over the same period. The bivariate conditional correlations between Malaysia, Philippines and Taiwan have remained relatively stable over the sample period. Malaysia has continued to manage its exchange rate in an active manner since September 2, 1998, when the Malaysian authorities quite openly fixed their bilateral USD exchange rate, and have defended this parity through sterilized foreign exchange market interventions. This exchange rate policy is reflected in the drop in correlation with China after the Malaysian Central Bank’s announcement, followed by stabilization of the coefficient at values close to 0. In contrast to this, both the Philippine Peso and Taiwan Dollar were floated, on March 15, 1998 and April 3, 1989 respectively, and display relatively strong interdependence with China over the whole sample. In particular, the daily correlations fluctuate around 0.22 in the case of Philippines and around 0.31 in the case of Taiwan. It would appear that the correlation structure of those countries with respect to China has not changed significantly since adoption of a flexible exchange rate regime.

Finally, after the Chinese exchange rate regime change in July 2005, the time-varying conditional correlations of some countries show a distinct drop. This change appears to be particularly relevant for Hong Kong. While the RMB was delinked from the USD, Hong Kong has continued its currency board system which is designed to respond automatically to fund flows in and out of Hong Kong and maintain a stable exchange rate between the Hong Kong dollar and the USD. Thus far, our analysis must be accompanied by one important caveat: the discussion has focussed on estimation of time-varying co-movements across countries, while abstracting from the economic forces that may bring about these volatility spillovers. This raises a number of valid questions which must now be tackled: What are the factors that cause such co-movements? Are they regional in nature or can they be traced to specific developments in individual countries? These issues are discussed in the next section.

5. Economic fundamentals and cross-country co-movements

The evidence of cross-country heterogeneity with respect to NDF market correlations with China discussed in Section 4 can seem bewildering at first glance: for some countries the average conditional correlations are large, while for others they are close to zero. What factors help to explain the degree of heterogeneity in the magnitudes of the co-movements? And through which channels does the transmission process take place? A related fundamental problem with the econometric approach is that the non-zero. What factors help to explain the degree of heterogeneity in the magnitudes of the co-movements? And through which channels does the transmission process take place? A related fundamental problem with the econometric approach is that the non-zero. What factors help to explain the degree of heterogeneity in the magnitudes of the co-movements? And through which channels does the transmission process take place?
to adopt a certain exchange rate regime. In order to mitigate the reverse causality, or endogeneity problem, we have used indicators dated 1998.\footnote{In the previous sections we adopted an empirical-based modelling approach. The economies in question, however, are characterised by a high degree of simultaneity and forward-looking behavior, and are subject to changing policy regimes and policy rules. In the context of a reduced-form model, it is therefore difficult to infer a cause and effect relationship.}

The prime candidate expected to influence these cross-country co-movements is trade. Greater trade integration enhances financial market interdependence, as is apparent when a devaluation in one country temporarily increases its competitiveness, and thus also adversely affects its trading competitors.\footnote{The role of trade as a catalyst of co-movements was originally highlighted in to the context of currency crises. See, for example, Glick and Rose (1999). Using a common factor model, Forbes and Chinn (2004) test the trade channel and other potential determinants of comovements also for non-crisis periods. They find that both trade and financial linkages have played important roles since the mid 1990s. Furthermore, their paper shows that regional spillovers can occur, emanating from the largest economy and spilling into smaller countries in the region.} This mechanism is likely to have become relatively more important as a result of the removal of trade barriers and increasing degree of integration in recent years. This is borne out by the fact that trade flows between China and other Asian countries soared between 2000 and 2005. All in all, the role of China within Asian intra-regional trade is still difficult to define with precision. Commentators’ views on this Chinese role can be regarded as falling into two distinct categories.\footnote{For a more detailed discussion see, e.g., Ahearne, Fernald and Loungani (2003).}

According to the first line of thought, China and other Asian economies share mutual benefits from the increased incomes of Chinese consumers, as well as from the potential for greater integration of product lines across the region, both of which are reflected in the expanding intra-regional trade in Asia. The contrasting view sees China and emerging Asia as competitors, specializing in the production of export goods that are relatively close substitutes which compete for market share in major export markets. Our findings appear to support the former of these viewpoints: from the two plots on the first row of Fig. 5 it appears clear that trade openness can indeed be considered a plausible explanation for the degree of interdependence between Asian countries and Chinese NDF market returns, as higher export countries are also those with the higher correlation coefficients (Hong Kong, Korea, Taiwan).\footnote{The majority of FDI flowing into China originates from Hong Kong and Taiwan. Zhang (2005) has analysed and identified various determinants of this dominant Hong Kong and Taiwan direct investment.}
One would also expect financial integration impact the extent of linkage between Chinese and other Asian NDF markets. Over the last 20 years, East Asian economies have promoted financial integration by liberalizing their capital account and financial sector through the relaxation of financial regulations. Financial openness can be quantified using a variety of measures: in Fig. 5 we employ both bilateral country-to-country FDI flow, a quantity-based measure of cross-border financial intensity, and total FDI as measures of capital account openness. From the two plots on the second row of Fig. 5 it appears that countries with greater exposure to bilateral capital flows with China, such as Hong Kong, Taiwan and Korea, experience stronger interdependence among NDF markets compared to countries where bilateral FDI inflows are of relatively smaller magnitude. Viewed as a whole, our results suggest that the magnitude of co-movements between the renminbi and other Asian-currency NDF contracts is indeed related to the degree of real and financial integration.29

A further issue worth exploring when analysing the determinants of cross-country differences in correlation coefficients is the type of exchange rate regime operating in each country. Empirical analysis seeking to uncover the link between countries’ exchange rate regimes and their macroeconomic performance depend critically on how the regimes are classified.30 The official (de jure) IMF exchange regime classification categorizes member’s exchange rate regimes based on their official reports to the IMF. The exchange rate regime declared by a country, however, often differs from its operational regime. In East Asia, both crisis-hit countries, including Korea, Indonesia, Thailand, and non-crisis countries such as Singapore and Taiwan, officially announced a particular exchange rate regime but in reality most of them possess substantially less exchange rate flexibility than they have reported. In recognition of this problem, the IMF has moved to a de facto classification since January 1999. This new classification combines available information on the exchange rate, monetary policy, and authorities’ formal or informal policy intentions with data on actual exchange rate and reserve movements to reach a judgment on the actual exchange rate regime in operation. Besides

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29 One striking finding to emerge from the second row of Figure 5 is that the degree of integration with the rest of the world in its entirety appears to play as important a role as bilateral integration with China in explaining the correlation coefficients.

30 It is not our purpose to evaluate the success of specific exchange rate regimes in meeting their stated objectives, nor do we claim to judge the impact of alternative regimes on macroeconomic performance and social welfare dimensions beyond these regimes’ influence on volatility transmission.
the IMF, several authors have developed alternative systems of reclassifying exchange rate regimes. In particular, Levy-Yeyati and Sturzenegger (2003) defined de facto exchange rate regimes according to the behaviour of three classification variables: exchange rate volatility, the volatility of exchange rate changes, and the volatility of international reserves. They identify four exchange rate regime categories: the first and the second category corresponding to a pure and a dirty float, respectively, the third one to a crawling peg and the last category corresponding to a fix peg. A more elaborated classification was developed by Reinhart and Rogoff (2004) who incorporated data on parallel and dual exchange rate markets, arguing that market-determined exchange rates are better indicators of the underlying monetary policy than the official exchange rate. The classification they obtained differs substantially from previous attempts at reclassifications and it consists of six categories, ranging from currency board (category 1) to freely falling exchange rate regime (category 6).

In order to allow for a more nuanced assessment, we use alternative advances in the classification of exchange rate regimes to gain further insights into co-movements across regimes and consider both the de jure and de facto classification within our set of indicators.\textsuperscript{31} From the two plots in the first row of Fig. 6, which depict both the IMF classifications, no clear cross-country connection between exchange rate regime and degree of interdependence appears to emerge. Hong Kong and Malaysia, the only two countries with pegged currencies, exhibit the highest and lowest correlation coefficients with China, respectively, while the correlations of the other countries, possessing flexible regimes, range from the 0.11 (Indonesia) to the 0.25 (Korea). The picture obtained using the Levy-Yeyati and Sturzenegger (2003) classification (bottom left panel of Fig. 6) is substantially unchanged, whilst the degree of flexibility of the exchange rate regime and the cross-country comovements appear to be negatively connected when the Reinhart and Rogoff (2004) regime classification is considered (bottom right panel of Fig. 6. In other words, the more flexible the exchange rate, the lower the correlation coefficient with China.

Given that the results are highly dependent on the exchange rate regime classification used, the exchange rate regime cannot be regarded as a robust candidate for explaining the observed cross-country differentials in correlation coefficients.\textsuperscript{32}

6. Conclusions and further comments

At the heart of this paper lies one fundamental question: what linkages exist between Mainland China and other Asian economies? A thorough understanding of the dynamic properties of cross-market volatility transmission is vital for assessing the level of integration between markets, both for investment purposes and for increasing the capacity to produce reasonable forecasts. To this end, the analysis undertaken in this paper embarks on a hitherto untraveled route. In a context of growing interest in the Chinese renminbi’s future path, as well as in co-movements across Asian currencies, we focus on links between renminbi NDF exchange rates and those of other Asian countries and proceed to investigate the nature of the volatility spillovers across markets. In order to model the volatility transmission mechanism we estimate several multivariate GARCH models which allow for a time-varying correlation structure.

The empirical results of this study are threefold. Firstly, the estimates arising from our models highlight the presence of strong GARCH effects in virtually all of the regressions, with the sum of (statistically significant) estimated coefficients very close to one. This evidence implies that there are indeed volatility spillover effects between China and the other seven Asian NDF markets. Secondly, from the analysis of time-varying conditional correlations it emerges that the coefficients are all positive and display changes in their patterns throughout the time span under consideration. What is more, these coefficients tend to increase in magnitude towards the end of the sample period. Therefore, it would appear that renminbi NDFs have indeed been a driver of various Asian currency markets. It is also evident that such co-movements exhibit a substantial degree of heterogeneity across countries. As a final step, we identify three possible sources of such heterogeneity: degree of trade openness, degree of financial openness, and exchange rate regime. We analyze their roles in explaining the different correlation levels across countries. We find that it is the degree of real and financial integration that are the key conduits for volatility transmission.

One key policy implication, in particular, emerges from this paper: there exists clear evidence of renminbi externalities impacting on other Asian countries. Even if some countries have been clearly less affected by renminbi shocks than others, none can claim to have been completely immune from Chinese exchange rate shocks. From a broader perspective, closer integration with Mainland China would represent both an opportunity for further economic stimulus and a potential source of macroeconomic risk for the emerging economies of Asia. One would expect greater trade integration in Asia to facilitate the transmission of shocks between economies in the region, a reason being that China has become a source of demand for final goods produced in Asian countries. More generally, shocks to Mainland China’s economy are likely to resonate in the other Asian economies through confidence effects. By now, China’s economy has grown to such an extent and has become so integrated with the rest of Asia that investor sentiment toward emerging Asia depends to an increasing degree on the economic climate expected to prevail in China.

While we emphasize that this paper should rightly be regarded as an initial exploration into the role played by cross-market volatility transmission in the linkages that exist between Mainland China and other Asian economies, it is clear that the significance of this issue in understanding the economic interactions of the region cannot be underestimated. It is hoped that, once more comprehensive datasets become available, this paper will provide the platform from which a more meticulous study can be launched.

\textsuperscript{31} Exchange rate regime classifications for Taiwan are not available. Compared to de facto classification, the de jure classification overstates the number of true floats and pegs, suggesting that fewer countries are at the polar extremes than that implied by their official reports.

\textsuperscript{32} The small number of observations plotted in the scatter diagrams raises concerns about the robustness of the conclusions drawn. Due to these data limitations our results on potential determinants are indicative only. Additional evidence from other countries is required if one wishes to gain more detailed insights.
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