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DETERMINANTS AND DYNAMICS OF PRICE DISPARITY IN ONSHORE AND OFFSHORE RENMINBI FORWARD EXCHANGE RATE MARKETS

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Determinants and Dynamics of Price Disparity in Onshore and Offshore Renminbi Forward Exchange Rate Markets*

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Abstract

Price disparities between the renminbi onshore deliverable forward and offshore non-deliverable forward exchange rates is an intriguing puzzle in financial economics. This paper investigates the determinants of these price disparities focusing on the possibility of parameter uncertainty. In the presence of information asymmetry and market segmentation among onshore and offshore investors, it is possible that they formulate different views on the Mainland economy which translate into a different assessment of the outlook for Mainland interest rates. Through a no arbitrage condition that relates the forward rate to the spot rate and interest rate differential, a different assessment of the path of interest rates can lead to a different valuation of forward prices. We estimate a term structure model for the implied renminbi interest rate using a Bayesian approach, in which investors' model parameter uncertainty is represented by the posterior standard deviation of the volatility of the interest rate. We show that parameter uncertainty can help to explain price disparities, in addition to market-wide aggregate uncertainty and illicit capital flows in the Mainland's balance of payment.

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1. Introduction

The offshore financial market in Hong Kong helps the development of the Mainland's trade and financial integration with the rest of the world in the absence of full liberalization of its capital account. However, the institutional separation between onshore and offshore financial markets has led to disparities in the price of some financial assets. Prominent examples are A- and H-shares[1] in the equity market, the onshore deliverable and offshore non-deliverable renminbi forward exchange rate, and the onshore and offshore renminbi spot exchange rate. There has been a lot of research into price disparities in Chinese equity markets,[2] but little study of disparities in the foreign exchange market. This paper helps to fill this gap by investigating price disparities in the renminbi forward exchange rate market.[3]

The renminbi non-deliverable forwards (NDF) have been mainly traded in the over-the-counter market in Hong Kong since 1996. It enables international investors to hedge their renminbi exposure as well as allowing currency traders to take positions for market-making and speculative purposes. The settlement rules for NDF and deliverable forwards (DF) are different. The two counterparties of a NDF contract settle the transaction, not by delivering the underlying pair of currencies as in a DF contract, but by making a net payment in a convertible currency (typically the US dollar) proportional to the difference between the agreed forward exchange rate and the subsequently realised onshore spot rate at maturity. So, despite the fact that NDF are traded offshore, their pricing is linked to movements in the onshore spot rate.

The level of trade as a proportion of GDP has risen dramatically on the Mainland, reflecting entry into the World Trade Organisation in 2001 and revaluation of the renminbi on 21 July 2005 which has helped to promote the use of the renminbi as an international currency. Increased trade volumes and fluctuations in the renminbi exchange rate have, in turn, led to higher demand for hedging instruments in the onshore market. Following a series of policy initiatives by the Mainland authorities[4], DF have been traded in the onshore market since late-2005 but are still not accessible to offshore market participants. The level of daily transactions in the renminbi forward market is high. According to the 2010 Triennial Central Bank Survey of Foreign Exchange and Derivative Market Activity conducted by the Bank for International Settlement (BIS), the renminbi forward market is very liquid, with daily

[1] The A- and H-shares refer to shares issued by the Mainland's firms, which are allowed to list their shares in both the Mainland (A-share) and Hong Kong (H-share) stock exchanges. The shareholders of the A- and H-shares have the same voting rights and dividend payments, but their respective markets are segmented by the institutional barrier, as individual foreign investors are not allowed to purchase A-shares directly. Similarly, the Mainland individual investors are not allowed to purchase H-shares in Hong Kong.

[2] For recent studies on the price disparity in the Chinese equity markets, see Fernald and Rogers (2002), Wang and Jiang (2004), Chan and Kwok (2005), Arquette et al. (2008), Cai et al. (2011) and Chung et al. (2011).

[3] Although there is also notable price disparity in the renminbi spot rates, the time series of the offshore CNH market is not sufficiently long for analysis as the offshore CNH market was set up in August 2010.

[4] For a description of the development in the offshore and onshore renminbi derivative markets, see Peng et al. 2006).

turnover reaching USD 13.5 billion for the outright forwards.[5] However, as the onshore and offshore markets are segmented by an institutional barrier with limited arbitrage opportunities, there are notable price differences between the DF and NDF rate. Figure 1 shows the 1-month DF and NDF rates, with the disparity measured by their absolute difference in the period January 2006 to September 2011. Despite integration of the onshore and offshore markets, price disparities in the renminbi forward rates continue to exist, and can be particularly large during periods of market turbulence.

This paper attempts to explain these price disparities by developing a model for the renminbi forward exchange rate which allows for parameter uncertainty. Our model shares the theoretical insight from Pastor and Veronesi (2003) that investors are unsure about model parameters. In their model, investors' inability to pin down a firm's average profitability can rationalise the technology boom in the late-1990s without resorting to explanations based on speculative bubbles. Cremers and Yan (2010) and Korteweg and Polson (2010) find that investors' uncertainty about firms' asset values and their volatility can account for a large portion of credit spreads in the US corporate bond market. In this paper, the renminbi forward exchange rate per a unit of US dollar is linked to its spot rate and the renminbi-US dollar interest differential through the no arbitrage condition. Because of capital controls and the complexity of the Mainland's monetary policy, it is not straightforward to extract information about the monetary stance from the Mainland's interest rate term structure.[6] Instead, we postulate that investors make use of a pricing model to form their own assessment about the People's Bank of China's monetary stance. The implied renminbi interest rate is constructed using spot exchange rate information so it also reflects the economic fundamentals of the Mainland economy.[7] As a result, the implied interest rate also reflects the extent to which investors form different assessments about the Mainland economy, including their view on projected of GDP, CPI and money growth, etc. We model investors' views using a Bayesian framework in which they have to infer the posterior distribution of model parameters by solving a filtering problem, given their prior beliefs over the model parameters and the observed data (e.g., historical prices, news and published reports). If there are differences in the information sets of onshore (Mainland) and offshore (Hong Kong and international) investors, this would be reflected in different assessments of the underlying economy through different estimated parameters.

5 The BIS survey gathers transaction data for major currencies reported by the corresponding central banks, which could significantly deviate from the estimates provided by the market participants. For example, the Financial Times once reported that the average daily turnover for the NDF was between USD 3 – 5 billion in March 2010.

6 In the US, numerous researches have indicated the predictive power of the term structures in gauging the Fed's monetary policy stance and its credibility in monetary policy. The Fed only controls the very short end of the term structure as its monetary target, while market forces determine the yields at longer maturities. Typically, market forces and the evolution in the shape of the term structure can provide information about the Fed's policy stance (see Goodfriend (1998) for a survey). On the contrary, the People's Bank of China sets the level of the interest rate across different maturities, which makes it difficult for market participants to use techniques developed in their study of the US term structures to gauge the Mainland's policy stance. Furthermore, the Mainland authorities also indirectly control the growth of money supply through quota limits of loans granted by financial institutions.

7 Engel et al. (2008) provide conditions on how the nominal exchange rate is related to the fundamentals.

Using daily exchange rates and interest rates data over the sample period from January 2006 to September 2011, we model the implied renminbi interest rate using the Vasicek (1977) model and estimate its parameters on a non-overlapping monthly basis using the Bayesian method. The Vasicek model is an equilibrium term structure model based on assumptions about economic variables and yields a process for the short-term risk-free rate. The corresponding bond prices can be implied from the process. The Vasicek model specifies that interest rates are pulled back to some long-run average level over time (i.e., a mean-reverting process). Superimposed upon this "pull" is a normally distributed stochastic term which gives rise to model parameter uncertainty in our study.

Considering the Bayesian methods, we estimate the Vasicek model by the Bayesian Markov Chain Monte Carlo (MCMC) method based on the joint posterior distribution of model parameters. The joint posterior distribution, however, is usually a high dimensional object which precludes any efficient sampling algorithm. The use of the MCMC method can circumvent this problem by decomposing the complicated joint posterior distribution into a hierarchy of conditional posterior distributions, which makes the sampling feasible. According to Bayes' theorem, these posterior distributions provide a summary of the dispersion in investors' prior views as reflected by the observed historical data.[8] Given that the mean-reverting parameters are long-run estimates, the posterior standard deviation of the estimated volatility, which summarises the extent of investors' disagreement in their views about the Mainland economy, is used to measure the extent of parameter uncertainty. Regression analysis shows that parameter uncertainty is a robust variable in explaining price disparities, in addition to market-wide uncertainty and illicit capital flows in the Mainland's balance of payment.

This paper follows the work of Fan and Johansson (2010), Hong et al. (2010), and Cheung and Qian (2010). Fan and Johansson (2010) find that there is a stochastic component in the renminbi interest rate, which provides support for our modelling assumption that the renminbi interest rate is stochastic. Hong et al. (2010) compare estimates from different stochastic specifications for the renminbi interest rate. Cheung and Qian (2010) study deviations from covered interest rate parity in the case of China and identify an explanatory set of variables.

This paper is organised as follows. Section 2 describes a model of renminbi forward exchange rate determination, illustratrating how parameter uncertainty can arise. Section 3 shows how to estimate the model using the Bayesian method. Section 4 discusses the data used in this study and examines the relationship between price disparities and parameter uncertainty based on regression analysis. Section 5 concludes.

[8] The Bayes theorem states that the posterior probability is proportional to the product of the prior probability and the likelihood given by the data.

2. A Model of Forward Exchange Rate Determination

The interest rate differential between the renminbi (RMB) and the US dollar (USD) can be linked to the forward and spot rates of the renminbi through a no-arbitrage condition as follows:

$$F(t,T) = S(t)\frac{B_{USD}(r_{US},t,T)}{B_{RMB}(r,t,T)}, \tag{1}$$

In Eq. (1), *S* is the spot rate of the renminbi at time *t* and $F(t,T)$ is the forward exchange rate at maturity *T*. B_{USD} and B_{RMB} are the risk-free bond prices with short-term interest rates r_{us} and r in the US and Mainland China respectively. We further assume that the US bond market is liquid which allows us to invert the bond prices $B_{USD}(r_{US},t,T)$ into observable interest rates. The renminbi interest rate, by contrast, cannot be derived from observed bond prices because there are limited arbitrage opportunities for offshore investors to buy or sell renminbi bonds. Instead, we assume information about the renminbi interest rate can be extracted from observed exchange rates and the US interest rate through Eq. (1). Investors' uncertainty about the renminbi bond price in Eq. (1) arises because they need to have a bond pricing model based on their assessment about the future path of renminbi interest rates. Specifically, they use the Vasicek (1977) bond pricing model to convert the renminbi bond price to a process for short-term renminbi interest rates and its associate model parameters, especially interest rate volatility.[9] The Vasicek model allows for a negative interest rate which is an advantage in modelling the short-term interest rate implied by the renminbi spot and forward exchange rates.[10] Reflecting expectations of a large appreciation of the renminbi, the market priced in a substantial premium of the forward rate over the spot rate during our sample period. This requires a substantial interest rate differential in order to be consistent with Eq. (1). The expectation of a renminbi appreciation was so firm that Eq.(1) generates negative renminbi interest rates. The stochastic process for the renminbi interest rate is specified under the Vasicek model as

$$dr = \kappa(\theta - r)dt + \sigma dW_t^P, \tag{2}$$

where *dr* represents the change in the renminbi interest rate, *κ* determines the speed of adjustment towards a long-run mean of *θ, σ* is the volatility of the interest rate and dW_t^P is a standard Brownian motion under the physical measure *P*. If we denote λ as the market price of risk, we can rewrite the stochastic process in Eq. (2) under the risk-neutral measure *Q* as:

9 Given the assumption that the US bond prices and its yields can be inverted without measurement errors, the renminbi interest rates can be inferred by Eq. (1) when data for the renminbi forward and spot exchange rates and US interest rates are available.

10 Other equilibrium term structure models with a square-root process such as the Cox–Ingersoll–Ross (1985) model can be used to model the renminbi short-term interest rate. However they do not allow negative interest rates.

$$dr = \kappa\left(\tilde{\theta} - r\right)dt + \sigma dW_t^Q, \tag{3}$$

where $\tilde{\theta} = \theta - \kappa^{-1}\sigma\lambda$. Under the risk-neutral measure Q, the well-known closed-form solution for bond price $B_{RMB}(r,t,T)$ is

$$\begin{aligned} B_{RMB}(r,t,T) &= B_{RMB}\left[r\left(\sigma,\kappa,\tilde{\theta}\right),t,T\right] \\ &= E_t^Q\left[\exp\left(-\int_t^T r_s ds\right)\middle|\sigma,\kappa,\tilde{\theta}\right], \\ &= \exp\left[A(t,T) + D(t,T)r\right] \end{aligned} \tag{4}$$

where

$$\begin{aligned} A(t,T) &= \left(\tilde{\theta} - \frac{\sigma^2}{2\kappa}\right)\left[D(t,T) - (T-t)\right] - \frac{\sigma^2 D^2(t,T)}{4\kappa} \\ D(t,T) &= -\frac{1-\exp\left[-\kappa(T-t)\right]}{\kappa} \end{aligned}.$$

In Eq. (4), we denote $B_{RMB}(r,t,T) = B_{RMB}\left[r\left(\sigma,\kappa,\tilde{\theta}\right),t,T\right]$ to stress that the bond price is an implicit function of the renminbi interest rate *r* which is determined by the model parameters σ,κ and $\tilde{\theta}$. That is, when investors know the model parameters that characterise the interest rate process with certainty, they can obtain the Mainland bond price by Eq. (4). In principle, once investors know the Mainland bond price, together with the US bond price and the spot rate, they can use Eq. (1) to formulate their view about the renminbi forward rate.

In reality, the model parameters are not observable and investors are uncertain about their true value. Instead, investors use publicly available data such as macroeconomic data and forecasts, or any beliefs, news and views regarding the Mainland economy to estimate the parameters. Different values for the model parameters in the pricing formula of Eqs. (1), (4) would yield different forward rates. Based on this observation, we postulate that the disparity in the forward rate can be generated by a dispersion of views on interest rate volatility σ, due to the presence of parameter uncertainty. From the perspective of a Bayesian econometrician, the dispersion in investors' views and parameter uncertainty about interest rate volatility σ is naturally captured by the posterior distribution $p\left(\sigma\middle|\kappa,\tilde{\theta},\Omega_t\right)$, conditional on other model parameters and the information set Ω_t generated by the observed equity prices at time t.[11] It is noteworthy that Eq. (1) is an equilibrium condition derived from a no arbitrage condition. Cheung and Qian (2011) argue that any substantial deviation from Eq. (1)

[11] The characterisation of the posterior distribution will be given in Section 3.

must partly reflect the extent to which the Mainland's capital controls are effective. It is therefore natural to wonder whether the disparity in the onshore and offshore forward rates is also due to the effectiveness of the Mainland's capital controls, instead of differences in model parameters. Despite adequate cross-border capital mobility on the Mainland, there are still limited arbitrage opportunities for institutional investors who have obtained the QDII and QFII quota. In principle, these investors would ensure Eq. (1) holds on average, perhaps with exceptions during market turbulence when funding liquidity and counterparty risk is high.[12] Although the resulting implied renminbi interest rate is influenced by the effectiveness of Mainland's capital controls, we show in Section 4 that parameter uncertainty remains a significant factor in explaining price disparities, even after controlling for the illicit capital flows in the Mainland's balance of payments (as a proxy for the effectiveness of capital control).

We provide a simple numerical example to illustrate how parameter uncertainty is related to price disparities in the renminbi forward exchange rate market. In particular, we assume that there is parameter uncertainty in the volatility of the interest rate process.[13] We set $S = 6.3, B_{USD} = 1, \kappa = 0.25, \theta = r = 0.05, \lambda = 0, T - t = 1/12.$ The first two parameters indicate that the spot rate of the renminbi per one unit of US dollar is 6.3 and that the US bond price is 1, by normalisation. The next three parameters jointly specify the dynamics of the interest rate process under the Vasicek model. Without loss of generality, the current interest rate is set at its long-run level. Finally, the market price of risk is assumed to be 0 and the time-to-maturity is one month.

Figure 2 illustrates the pricing function implied by the model and shows that the relationship between the forward rate and interest rate volatility is negative.[14] For illustrative purposes, we can separately identify interest rate volatility as perceived by a Mainland investor σ_{China} and a Hong Kong investor σ_{HK}. If $\sigma_{HK} > \sigma_{China}$, other things equal, the forward rate F_{HK} valuated by the Hong Kong investor would be lower than F_{China} valuated by the Mainland investor, i.e., $F_{HK} < F_{China}$. Moreover, a larger dispersion in the volatility implies a larger disparity in forward rates: when the difference in volatilities

12 Baba and Packer (2009) and Hui et al. (2011) find that the deviation of Eq. (1) is related to funding liquidity and counterparty risks.

13 We only allow parameter uncertainty of the interest rate volatility parameter in this study. Our justification for this assumption rests on the extent of errors in estimating the diffusion process in Eq. (2). While Ball and Torous (1996), Philips and Yu (2005) and Tang and Chen (2009) find that the estimation of the drift parameters (i.e., κ and $\tilde{\theta}$) can incur large biases and volatility can usually be accurately estimated, our study assumes that estimation errors are relatively small compared with the extent of disagreement in investors' perceptions.

14 By combining Eq. (1) and Eq. (4), it can be shown that $\frac{\partial F}{\partial \sigma} = -\frac{B_{USD}}{[\exp(A + Dr)]^2}\frac{\partial A}{\partial \sigma}$, where $\frac{\partial A}{\partial \sigma} = \exp(A + Dr)\left\{\left(-\frac{\lambda}{\kappa} - \frac{\sigma}{\kappa}\right)[D - (T - t)] - \frac{\sigma D^2}{2\kappa}\right\}$. Under our assumed parameter values, we have $\frac{\partial A}{\partial \sigma} > 0$ and this means bond prices and volatility are positively related. However, in a more general diffusion setup, the sign of this partial derivative is generally ambiguous. For a detailed treatment in the comparative statics of bond prices under a general multifactor diffusion setting, see Mele (2003).

$(\sigma_{HK} - \sigma_{China})$ increases from 10% to 35%, price disparity in the renminbi forward rate market $(F_{HK} - F_{China})$ increases from RMB0.12 to RMB0.45 per one unit of US dollar. This implies a positive relationship between the dispersion of views on interest rate volatility and the size of price disparities using the Vasicek model with parameter uncertainty. In the empirical application of the model, although the level of volatility used by individual investor is unknown, the degree of parameter uncertainty can still be measured by the dispersion of the posterior distribution as estimated using the MCMC method. We take the posterior standard deviation of interest rate volatility as the measure of parameter uncertainty.

It is important to emphasise that it is not possible to infer individual investors' estimates of the model parameters based on observed market data only. While the estimated posterior distribution captures the dispersion in investors' view and degree of parameter uncertainty, it is an aggregate measure that summarizes the inhomogeneity in the information sets of individual investors. Moreover, it potentially incorporates other important risk factors and constraints that might influence the pricing decision made by the investors. In view of this, it is not possible to identify whether Hong Kong investors are more uncertain about the model parameter than Mainland investors, or vice versa. In the proposed framework, the reason why the NDF is traded at a premium over the DF is explained by a higher level of interest rate volatility anticipated by Hong Kong investors, and this phenomenon is not a result of higher parameter uncertainty (higher dispersion of interest rate volatility) in the Hong Kong market. In general, the degree of parameter uncertainty should be lower in the Mainland market, given the fact that its investors possess information advantages, especially institutional investors. Such intuition, however, cannot be verified in the framework as we cannot separately identify how much of the dispersion in the estimated parameter is contributed by Mainland and Hong Kong investors.

In the following section, we model investors' decision-making process using a Bayesian framework in which they have to infer the posterior distribution of model parameters by solving a filtering problem, given their prior beliefs over the model parameters and historical data. We assume that investors estimate the interest rate process in Eq. (2) from historical data and use the estimated parameters to form their valuation of the forward exchange rate. Following other empirical studies of term structure models, such as Longstaff and Schwartz (1992), Chan et al. (1992) and Bali and Wu (2006), we proxy the unobserved short-term interest rate by the one-month implied interest rate . By taking the perspective of a Bayesian investor, we are able to quantify the level of parameter uncertainty by the posterior standard deviation of σ (the interest rate volatility) as implied from the historical data.

3. Bayesian Estimation of the Model

This section explains how to estimate the interest rate process and obtain the measure of parameter uncertainty using the MCMC method. We approximate the continuous time diffusion process Eq. (4) based on the Euler discretisation as

$$r_t - r_{t-1} = \kappa\left(\tilde{\theta} - r_{t-1}\right)h + \sigma\sqrt{h}\varepsilon_t\,, \tag{5}$$

where $\varepsilon_t \sim N(0,1)$ and h is the sampling interval between observations. Given a time series of the renminbi interest rate $r^T = \{r_t\}_{t=1}^n$, we estimate the parameters of the model $\Theta = (\kappa, \tilde{\theta}, \sigma)$ using Eq. (5) and the MCMC method. Let $\pi(\Theta)$ denote the prior density for the parameters, applying Bayes' theorem and using the fact that ε_t follows a standardised normal distribution, we can write the posterior density as:

$$p\left(\Theta \middle| r^T\right) \propto \pi(\Theta) \times \prod_{t=1}^{n} \frac{1}{\sigma\sqrt{h}} \exp\left[-\frac{1}{2}\left(\frac{r_t - r_{t-1} - \kappa\left(\tilde{\theta} - r_{t-1}\right)h}{\sigma\sqrt{h}}\right)^2\right], \tag{6}$$

where the second term represents the likelihood function associated with Eq. (5). Eraker (2001) shows that by defining *y* to be a vector formed by grouping $r_t - r_{t-1} / \sqrt{h}$ and *X* to be a two by n matrix formed by stacking [$\sqrt{h} \quad \sqrt{h}r_t$] for all *t*, it is possible to rewrite Eq. (6) as the likelihood function of a linear regression model of *y* on *X*. A standard result in Bayesian econometrics yields[15]

$$\left(\kappa, \tilde{\theta}\right)\Big|\sigma, r^T \sim N\left(\varpi, \sigma^2\left(X'X\right)^{-1}\right) \tag{7}$$

and

$$\sigma^{-2}\Big|r^T \sim IG\left(n-2, s^2\right), \tag{8}$$

where $\varpi = \left(X'X\right)^{-1}\left(X'y\right)$, $s^2 = 1/n\sum_{i=1}^{n}\left(y_i - X_i\varpi\right)^2$, *N* and *IG* denote the multivariate normal and inverse gamma distributions respectively. We draw iteratively from Eqs. (7) and (8) 60,000 times and discard the first 10,000 burn-in samples. We conduct statistical inference (mean, variance, median, etc.) based on the sample from these remaining draws.[16]

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15 In deriving Eqs. (7) and (8), we assume a noninformative prior for the parameters. The joint prior is $\pi(\Theta) \propto 1/\sigma^2$.

16 The market price of risk λ is set to zero in our estimation. There are two justifications for this assumption: 1) The time series of the implied interest rate is too short to get a precise estimate for the market price of risk; and 2) The market price of risk does not affect the volatility estimate (see Eq. (8)), and therefore does not affect the measure of parameter uncertainty.

4. Data and Empirical Analysis

In this section, we describe the data used in this study and investigate the relationship between parameter uncertainty and price disparities through a regression model. We test the hypothesis that parameter uncertainty is a separate factor in explaining price disparities after controlling for other macroeconomic and financial factors.

4.1 Data

We construct a dataset of monthly frequency over the sample period from January 2006 to September 2011. All the data used in this study are obtained from Bloomberg and CEIC. For each trading day, daily values on the one-month renminbi NDF and DF rates are used to construct a price disparity series, defined as the absolute difference between the NDF and DF rates.[17] Daily disparities are averaged on a monthly basis to construct the price disparity series used in the regressions. The daily NDF rates, together with the renminbi-US dollar spot rates and the US LIBOR of the one-month maturity are used to construct the implied renminbi interest rates by $r = r_{us} - (\ln F - \ln S) \times 12$. The implied daily renminbi interest rate serves as a proxy for the short-term interest rate and is used as an input in the estimation of the term structure model for each non-overlapping month. Although the NDF is traded in the offshore market and made available to international investors, it is still priced with reference to the onshore renminbi spot rate. As a result, the dynamics of this term structure should be associated withonshore interest rate volatility arising from unobserved monetary conditions in the Mainland, which is potentially affected by prospects for the Mainland economy. This gives us ameasure of the extent to which offshore and onshore participants in the market differ in their views about the future performance of the Mainland economy. From the MCMC estimates in each month, we obtain the posterior standard deviation of volatility as a measure of parameter uncertainty. Bayesian methods deal well with the problem of limited data points, and in our case we have just 20 observations in each month. In Bayesian statistics, if the likelihood revealed by the data is not informative enough, more weight is given to the prior distribution for the identification of parameters.[18] The interest rate obtained from the DF rate yields a similar measure of parameter uncertainty. Similar results are obtained when we use the US Treasury yield as a proxy for the US interest rate.

It is important to identify whether our “parameter uncertainty hypothesis” is a separate channel in our analysis. To test this, we control for the factors influencing the Mainland’s macroeconomic and financial conditions suggested by previous studies. Cheung and Qian (2010) argue that the balance of payment statistics and macroeconomic factors help to explain deviations from covered interest rate parity for China, as the direction of capital and trade flows can change appreciation pressure on the renminbi. Baba and Packer (2009) and Hui et al. (2011) find that funding liquidity and counterparty

[17] The one-month rate is one of the most commonly refereed rates quoted by market participants. We provide robustness checks for other maturities in the empirical analysis presented in Table 3.

[18] The prior distribution is given in footnote 13.

risks are important determinants for the dislocation in the foreign exchange swap markets for several currencies during the financial crisis of 2007-2009. Finally, Longstaff et al. (2011) show that market-wide risk factors usually explain a large portion of asset returns. In particular, we augment our regression model with the following control variables:

i. Volatility index (VHSI): We use the HSI (Hang Seng Index) volatility index as the measure of market-wide risk.[19] Of the 49 constituents of the HSI, 11 firms have their main operations in the Mainland. Thus, the HSI volatility index partly reflects market-wide uncertainty arising in the Mainland. Meanwhile, given its high correlation of about 90% with the Chicago Board Options Exchange Volatility Index (VIX), the HSI volatility index should also partly reflect market-wide uncertainty in global financial market. Typically, an increase in the volatility index corresponds to an increase in investors' aversion to market-wide aggregate uncertainty. It is useful to distinguish between market-wide aggregate uncertainty and parameter uncertainty. Parameter uncertainty concerns investors' inability to pin down the model parameters in the asset pricing formula. On the contrary, the volatility index measures investors' aversion to any uncertainty arising in financial markets. We may therefore view parameter uncertainty as a measure of investors' uncertainty for a particular financial instrument in a specific market, while market-wide uncertainty reflects market aggregate volatility.

ii. Capital flight (KF): In general, the direction and magnitude of a nation's trade and capital flows will affect the nominal value of its currency, but their influence is muted in the case of the renminbi because of capital controls. To factor out the effect of capital controls on the movement in trade and capital flows, we use a capital flight measure developed by Claessens and Naude (1993) to measure the component of capital flows that is illicit.[20] Intuitively, this measure captures residual flows after subtracting the nation's use of funds (which includes increases in foreign reserve and current account deficit) from its source of funds (which includes increases in foreign debts and net foreign direct investment) in the balance of payments. A higher level of capital flight is generally taken to indicate less restrictive capital controls which, in turn, helps to reduce market segmentation and price disparities.

iii. Credit default swap spread (CDS): In various studies that attempt to understand deviations from covered interest rate parity (CIP) in the foreign exchange swap markets, it is commonly found a country's political risk, transaction costs and capital market

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[19] The HSI volatility Index was launched in February 2011 and backdated its data to January 2006. The index use the option price of the HSI to track stock market volatility, following the methodology similar to that used for the Chicago Board Options Exchange Volatility Index.

[20] The flow of capital flight equals the sum of the change in external debts and the net foreign direct investment, and subtracts the current account deficit and the change in international reserves. The resulting flow series is then compounded by the LIBOR to obtain the stock of capital flight series used in our analysis. In constructing the capital flight series, some of the components are interpolated using the temporal disaggregation method by Chow and Lin (1971). For details, see the appendix in Cheung and Qian (2010).

imperfections play a role.[21] Baba and Packer (2009) and Hui et al. (2011) both argue that counterparty risk of banks is a significant factor explaining deviations from CIP of the US dollar during the global financial crisis of 2007-2009. It is possible that these factors may also explain price disparities, which increase during periods of financial market distress. Ideally, we would like to use the CDS spread of Mainland banks because they are the major participants in the foreign exchange market. However, there are only two Mainland banks which have active CDS contracts in our sample period.[22] To overcome this problem, we proxy the counterparty risk using the Mainland sovereign CDS spread. This assumption is justified by two reasons. First, although CDS spreads of banks are usually higher than that of their corresponding sovereign, their correlation is generally high because turmoil in the banking sector has been observed simultaneously with (quasi-) defaults in several countries.[23] Second, the Mainland government is the largest shareholder of the major Mainland banks.

iv. Funding liquidity risk (FUND): Theoretical work by Brunnermeier and Pedersen (2009) and empirical studies by Baba and Packer (2009) and Hui et al. (2011) point out that funding liquidity risk is an important element in understanding market liquidity and risk premiums. We use the one-month LIBOR-OIS (overnight index swap) spread as a measure of funding liquidity risk.[24]

v. The Mainland liquidity conditions (LIQ): In addition to funding liquidity risk, the liquidity condition in Mainland financial markets may also help to explain price disparities. We use the seven-day repo rate, a widely cited barometer, as a proxy for liquidity conditions in the Mainland.

Except for the capital flight variable, all of the above control factors (i.e., VSHI, CDS, FUND and LIQ) are monthly averages of the daily values of each variable. Table 1 provides summary statistics for the variables used in this study.

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21 See Officer and Willett (1979) for a survey.

22 The two banks are Bank of China and China Development Bank.

23 The correlation coefficient between the average of the two banks' CDS spread and the Mainland sovereign CDS spread is 98%.

24 The LIBOR-OIS spread generally reflects the funding liquidity risks in the interbank market and has been widely used by market participants and central banks to gauge funding liquidity conditions. An OIS is an interest rate swap in which the floating leg is linked to an index of daily overnight rates. The two parties agree to exchange at maturity, on an agreed fixed rate and interest accrued at the floating index rate over the life of the swap. The fixed rate is a proxy for expected future overnight interest rates. As overnight lending generally bears lower credit and liquidity risks, the credit risk and liquidity risk premiums contained in the overnight index swap rates should be small. Therefore, the LIBOR-OIS spread generally reflects the credit and liquidity risks in the interbank market.

4.2 Parameter Uncertainty and Price Disparity Regression

Figure 3 plots the trend of the posterior standard deviation of volatility obtained from the Bayesian estimation against price disparities. These move in tandem with our measure of parameter uncertainty, suggesting that the latter is a key determinant. It is noted that the size of price disparities and parameter uncertainty are usually small, and become larger only during periods of significant market turbulence (e.g., the default of Lehman Brothers in 2008).[25] To examine their causal relationship when the control variables are in place, we estimate the following regression:

$$\begin{aligned} DISPARITY_t = \beta_0 + \beta_1 DISPARITY_{t-1} + \beta_2 SD\sigma_t + \beta_3 VHSI_t \\ + \beta_4 KF_t + \beta_5 CDS_t + \beta_6 LIQ + \beta_7 FUND_t + \delta_t \end{aligned}, \tag{9}$$

where $SD\sigma$ denotes the posterior standard deviation of volatility and δ is the error term in the model. Because price disparities can persist, we include a lagged dependent variable in Eq. (9) to filter out auto-correlation in the regression.

The results are summarized in Table 2. The regression analysis shows that parameter uncertainty can explain the price disparities after controlling for macroeconomic and financial factors during the period between January 2006 and September 2011. The explanatory power of parameter uncertainty remains significant at the 1% confidence level and is not replaced by the set of additional variables. This supports our hypothesis that parameter uncertainty is a separate factor in explaining price disparities. A positive estimate of 54.31 implies that a one percentage-point increase in parameter uncertainty will be associated with an increase of around 54.31 pips in price disparities.

The regression explains 56% of the variation in price disparities. Capital flight shows a negative sign and explains a further 4% of the adjusted R-squared. A reduction in capital controls and a higher degree of arbitrage opportunities would reduce price disparities. VHSI explains an additional 3% variation of the price disparity. The explanatory power of parameter uncertainty remains significant at the 1% confidence level and is not replaced by the inclusion of VHSI. The implication is that investors' uncertainty about model parameters and the effect on price disparities is over and above any effects from more general market-wide aggregate uncertainty. In our theoretical framework, we model investors' uncertainty about renminbi interest rates, derived from exchange rate and US interest rate data, while the volatility index tracks option implied volatility in the stock market. It is therefore unsurprising that there is a spillover of uncertainty from the stock market to the bond and foreign exchange markets, given that financial markets are interconnected. Market-wide aggregate uncertainty usually increases during periods of market turbulence, resulting in a larger dispersion of views because of information asymmetries between onshore and offshore investors. This is, in turn,

[25] There was also a jump in the price disparity in October 2007 but it was rather short-lived. As a result, there was no apparent increase in our measure of parameter uncertainty. After all, the extent of uncertainty was not comparable to the default of Lehman Brothers in 2008, given that the volatility index was only hovered at a level of around 30 to 40 in late 2007, compared to a level of close to 70 after the default of Lehman Brothers.

reflected by higher parameter uncertainty which generates greater price disparities in our framework. Finally, the Mainland's CDS spread (CDS), liquidity condition (LIQ) and the funding liquidity risk (FUND) are estimated to be insignificant factors in explaining price disparities.[26]

We provide a robustness check on our model using data of price disparities with maturities of one week and three months respectively. For each maturity, the term structure model is re-estimated to derive a measure of parameter uncertainty. Eq. (9) is then re-estimated using the significant factors identified in Table 2. Table 3 reports the regression results which suggest that parameter uncertainty is a significant factor in explaining price disparities for both maturities.

5. Conclusion

The offshore renminbi forward exchange rate market provides a previously unavailable channel through which international investors can hedge, or even take a position on currency risk arising from fluctuations in the renminbi exchange rate. Because of capital controls, there is institutional separation between the onshore and offshore forward exchange rate markets. Despite increasing integration of the two markets in recent years, significant price disparities persist, and increase during periods of financial market distress. This paper argues that these price disparities may be related to differences in the views of onshore and offshore investors about monetary conditions on the Mainland. Using a forward exchange rate pricing model, investors' assessments are modelled by assuming that different investors use different model parameters in pricing the forward rates. The extent of their disagreement can be measured by the posterior standard deviation of the estimated parameters, which we use to measure the extent of parameter uncertainty. This paper finds that parameter uncertainty, in addition to market-wide aggregate uncertainty and illicit capital flows in the Mainland's balance of payments can help to explain price disparities.

The punch line of our framework is that even though individual investors use the same model to infer the renminbi forward exchange rate, a small difference in their estimates of model parameters would lead to different asset valuations. The result implies that price disparities are inevitable as long as investors have different assessments about the Mainland's monetary stance allowing for information asymmetries and market segmentation because of limited arbitrage opportunities. These disparities should reduce as the onshore and offshore financial markets become more integrated and the Mainland's capital account is liberalized.

[26] In an unreported regression without parameter uncertainty and VHSI act as control variables, funding liquidity risk is estimated to be a significant factor for the price disparity.

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Table 1. Summary Statistics of Variables in Eq. (9) from January 2006 to September 2011

Label	Variable name	Mean	Median	Max	Min	Std. Dev.
DISPARITY[1]	Price disparity (in pips)	138.45	122.35	448.50	18.91	92.52
SDσ[2]	Parameter uncertainty (in %)	1.70	1.42	6.77	0.41	1.08
CDS[3]	CDS spread	66.61	65.89	229.54	10.67	51.11
LIQ[4]	Seven-day repo (in %)	2.46	2.36	5.90	0.94	1.06
FUND[5]	LIBOR-OIS spread (in %)	24.69	10.25	265.27	4.73	38.11
KF[6]	Capital flight (in billion USD)	172.21	183.29	390.02	-2.11	101.25
VHSI[7]	Volatility index	28.86	23.97	70.55	14.94	13.11

Notes :
1. Price disparity is the monthly average of the absolute price differences (in pips) between the one-month onshore DF rate and the one-month offshore NDF rate.
2. Parameter uncertainty is the posterior standard deviation of the estimated volatility for the stochastic process in Eq. (5).
3. CDS spread is the monthly average of the five-year China's sovereign CDS spread.
4. Seven-day repo is the monthly average of the seven-day repurchase rate in the Mainland interbank market.
5. LIBOR-OIS spread is the monthly average of the spread between the one-month LIBOR and the overnight swap rate.
6. Capital flight is the sum of the following four items: (i) change in the Mainland's external debt; (ii) Net foreign direct investment to the Mainland; (iii) the Mainland's current account surplus; and (iv) increase in the Mainland's international reserves.
7. Volatility Index is the monthly average of the Hang Seng Index volatility.

Table 2. Determinants of Price Disparity in the Renminbi Forward Exchange Rate from January 2006 to September 2011

Variable	Coeff	t-Stat		Coeff	t-Stat		Coeff	t-Stat		Coeff	t-Stat	
Constant	3.4800	0.10		26.6436	1.39		41.7000	2.27	*	11.4186	0.77	
Lag disparity	0.1971	2.16	**	0.2301	2.82	***	0.3312	4.18	***	0.3581	4.88	***
Parameter uncertainty (SDσ)	54.3131	3.79	***	45.5269	5.24	***	52.5721	6.29	***	45.3392	5.09	***
Capital flight (KF)	-0.2110	-1.96	*	-0.2638	-4.16	***	-0.2226	-3.57	***			
Volatility index (VHSI)	3.1617	1.75	*	1.6631	2.01	**						
Funding liquidity risk (FUND)	-0.4909	-1.18										
Counterparty risk (CDS)	-0.3338	-0.95										
Mainland's liquidity condition (LIQ)	-2.1380	-0.23										
R-squared	61%			59%			56%			51%		
Adjusted R-squared	56%			57%			54%			50%		
Durbin-Watson stat	1.80			1.79			1.84			1.77		
No. of observation	68			68			68			68		

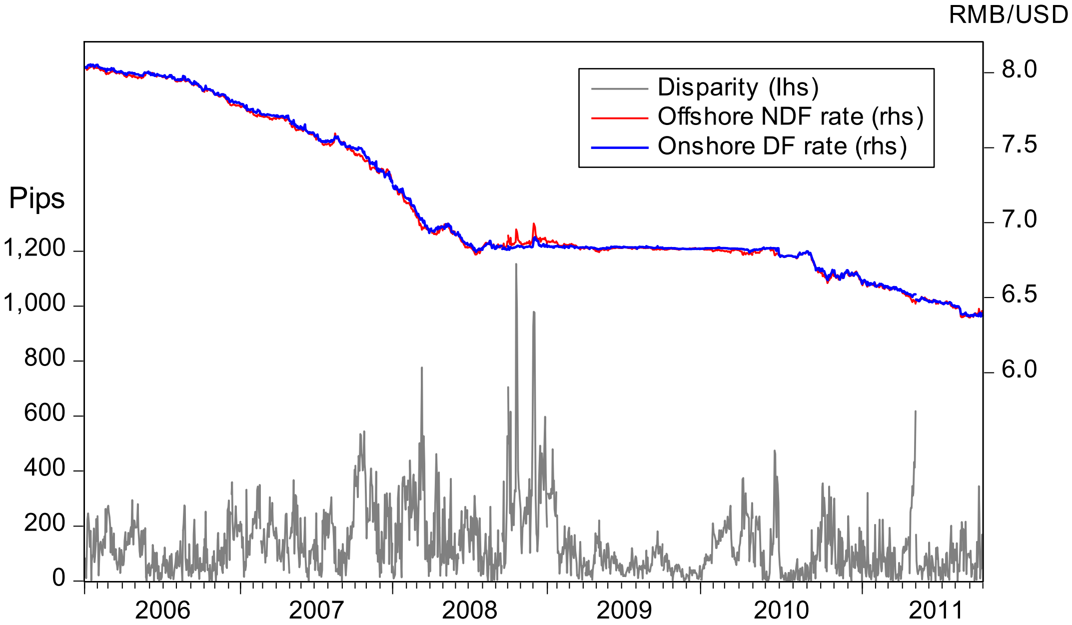
Note: Regression of the one-month NDF-DF price disparity on its own lag, the measure of parameter uncertainty (SDσ) and macroeconomic and financial factors (KF, VHSI, FUND, CDS, LIQ). The definitions of the variables are defined in Table 1. ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.

Table 3. Robustness Check of the Regression Model in Eq. (9)

	Dependent Variable					
	one-week price disparity			three-month price disparity		
Variables	Coeff	t-Stat		Coeff	t-Stat	
Constant	0.6950	0.09		113.2009	2.00	**
Lag disparity	0.2280	2.46	**	0.3486	4.70	***
Parameter uncertainty (SDσ)	5.5068	6.91	***	157.0095	3.18	***
Capital flight (KF)	-0.0337	-1.24		-0.6381	-3.43	***
Volatility index (VHSI)	0.7510	3.06	***	2.7641	1.56	
R-squared	63%			53%		
Adjusted R-squared	61%			49%		
Durbin-Watson stat	1.93			1.86		
No. of observation	68			68		

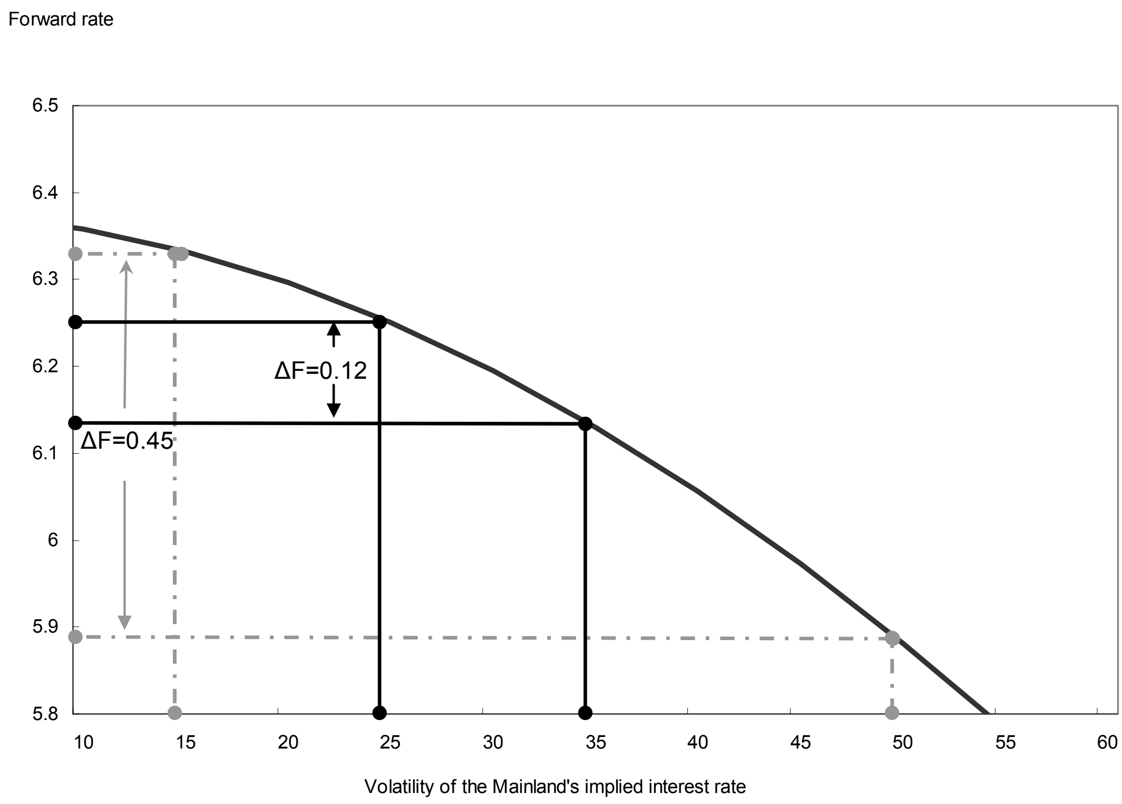
Note: Regressions of one-week and three-month NDF-DF disparity on its respective lag, parameter uncertainty (SDσ) and significant macroeconomic and financial factors (KF and VHSI) identified in Table 2. ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.

Figure 1. The Price Disparity in the Renminbi Forward Exchange Rate Markets



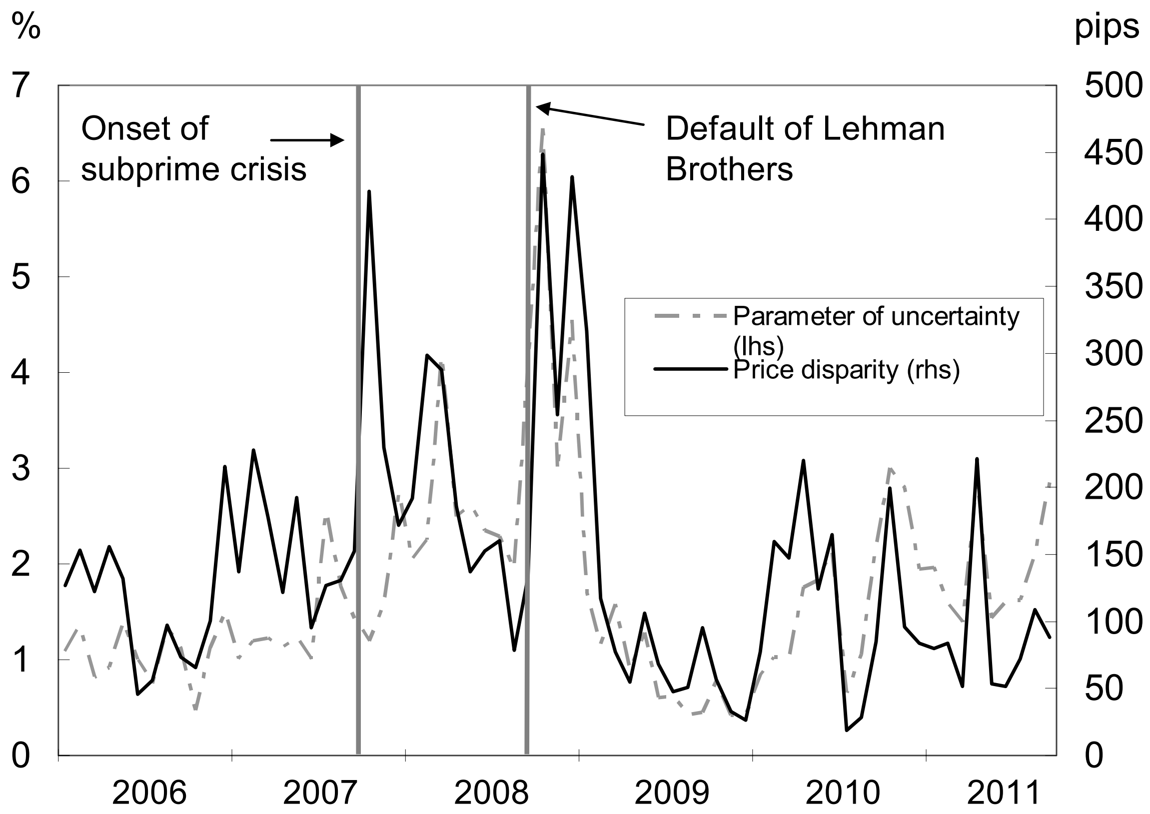
Note: This figure shows the one-month offshore non-deliverable forward (NDF) rate, the one-month onshore deliverable forward (DF) rate and their price disparity from January 2006 to September 2011. The disparity is defined as the absolute difference between the onshore and offshore rates.

Figure 2. Graphical Illustration of the Effect of Parameter Uncertainty



Note: This figure shows the theoretical relationship between the price disparity and the volatility parameter of the term structure model in Eq. (8). For illustrative purposes, we set the spot rate of renminbi per one unit of US dollar to 6.3, US bond price is normalised to 1, long-run mean of the interest rate is 5%, speed of adjustment parameter is 0.25 and the market price of risk is 0. *ΔF* denotes the change in forward rates

Figure 3. Dynamics of the Price Disparity and its Relationship with Parameter Uncertainty



Note: This figure shows the time series of the price disparity between the one-month NDF and DF rates and the measure of parameter uncertainty from January 2006 to September 2011.