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The information content in the offshore Renminbi foreign-exchange option market: Analytics and implied USD/CNH densities

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Abstract

In line with the deepening of the derivative foreign-exchange market in Hong Kong, we recover risk-neutral probability densities for future US dollar/offshore renminbi exchange rates as implied by exchange rate option prices. The risk-neutral densities (RND) approach is shown to be useful in analyzing market sentiment and risk aversion in the renminbi market. We include a forecasting exercise that confirms market participants were able to forecast the shape of the actual densities correctly for short horizons, even if their exact location could not be determined.

Keywords: offshore renminbi, options, risk-neutral densities, real-world densities, forecasting

JEL Classification: C53, F31, F37

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1 Introduction

The past five years have seen a significant increase in the international use and acceptance of the Chinese currency, the renminbi (RMB). For example, the government's promotion of the RMB as an invoicing currency for international trade and cross-border financial transactions has become an important channel for the internationalization of the Chinese currency.[1]

A number of reforms designed to liberalize the Chinese capital account have supported this rapid internationalization. The creation of offshore RMB clearing centers, where banking institutions officially appointed by the People's Bank of China (PBoC) handle clearing and settlement of RMB payments, facilitate RMB use in international trade and investment. A milestone in RMB internationalization was the RMB's inclusion in October 2016 in the basket of currencies that make up the IMF's Special Drawing Right (SDR) reserve assets. It was the first time that a new currency had been added to the SDR basket since the euro replaced the French franc and Deutsche mark in 1999. Although largely a symbolic move with limited market impact, it nevertheless helps fostering RMB globalization and cements the RMB's position on the international stage. The decision bolsters China's credentials as an emerging economic leader.

Despite the RMB's evolution into a major reserve currency, the liberalization process is likely to remain incremental in scope and significance. In practical terms, this means that RMB use will continue to be limited as an instrument for investment, asset allocation, and diversification management until the RMB reaches full convertibility.[2]

Foreign-exchange (FX) controls and regulations still require firms to separate RMB funds into *onshore* and *offshore* pools, resulting in two parallel currencies: the CNY (RMB held onshore) and CNH (RMB held offshore).

Over the past seven years, Hong Kong has become the global hub for RMB trade settlement, financing, and asset management. A wide range of RMB products and services are available. Given China's important role in the global economy, a more accessible CNH currency provides important opportunities for investors. The CNH is a freely traded, deliverable currency. While the

[1] The most recent triennial survey conducted by the Bank of International Settlements (BIS) in April 2016 found that overall RMB daily trading volume was USD 202 billion, almost double the volume of USD 120 billion posted in April 2013. During the period, the RMB's ratio of global foreign-exchange trading over the period increased from 2% to 4%. The Chinese currency ranked eighth globally in terms of international usage.

[2] See Eichengreen and Kawai (2015). An excellent sign of progress is Shanghai's Pilot Free Trade Zone (FTZ). It serves as a testing ground for the RMB's next step in international acceptance moving along the spectrum of capital account convertibility to free RMB convertibility. The Shanghai FTZ offers numerous advantages to firms, including ease in moving cash on and offshore. In particular, the Chinese authorities have made it easier to channel liquidity into mainland operations and sweep funds out of China.

CNH market is driven by supply and demand with no direct interference, the Hong Kong Monetary Authority (HKMA) closely monitors the CNH market. The HKMA also has put in place measures to provide liquidity assistance to banks in certain circumstances.

The HKMA is ready to provide RMB funding via its RMB liquidity facility with a view to facilitating long-term development of the offshore RMB business in Hong Kong. The HKMA injects RMB liquidity facilities in direct response to eligible requests of banks. It has designated nine banks as Primary Liquidity Providers (PLPs) for expanding their market-making activities for various CNH products. Banks earlier drew upon RMB liquidity from HKMA during periods of market stress, but today the total PLP funding facility is around RMB 18 billion. This level of liquidity support is sufficient to help banks smooth interbank market operations and enhance confidence in the offshore CNH market.

The PBoC steers the value of the onshore currency (CNY). Officially, the RMB is allowed to fluctuate in a range of ± 2 percent from the daily fixing rate. Initially the daily fixing was determined comparing quotes submitted by market-making banks against the closing spot rate of the previous day and market supply and demand. In May 2017, the authorities adjusted their guidance to banks, requiring them to include with their quotes a “countercyclical adjustment factor” with a view to reducing “irrational” depreciation expectations and “pro-cyclical” herding behavior. This undefined adjustment factor allows an opaque system that gives authorities wide discretion. At the same time, however, there is a sizeable arbitrage channel between mainland China and Hong Kong that typically keeps the gap in the trading prices of CNH and CNY fairly small. In essence, the CNH has become an effective proxy for the onshore CNY.[3]

The CNH market in Hong Kong has been very active in recent years. The CNH FX over-the-counter option market has seen significant growth in turnover, sophistication of option products, and market participation. Two trends have supported growth of the CNH FX option market: substantial growth in CNH turnover as the RMB has been progressively adopted as the *settlement/invoice currency for cross-border trade*, and rapid development in the *CNH structured FX products market*.

[3] Prior to 2012, there were more frequent divergences between the CNY and the CNH spot rates. This caused observers to question the reliability of the CNH as a proxy for the CNY movements at that time. As a consequence, the Chinese authorities made changes to the offshore trade settlement scheme in March 2012, the increase in trading via increased Qualified Foreign Institutional Investor (QFII) quotas and the introduction of the Renminbi Qualified Foreign Institutional Investor (RQFII) structure narrowed the gap of exploitable arbitrage opportunities between onshore and offshore markets. See Funke et al. (2015).

The burgeoning CNH FX option and structure products market marks the start of what might be deemed the "market sophistication" stage. The new market development stage is underpinned by rapid product innovation and increased market liquidity.[4] The new option products provide opportunities for investors to adopt different investment strategies for their RMB exposure.

Against this background, the paper is organized as follows. Section 2 gives an overview of the theoretical relationships between option prices and risk-neutral densities (RNDs) and real-world densities (RWDs) that form the basis of our application. Section 3 shows the results from estimated densities. While this type of analysis has become increasingly popular in recent years, no attention has, to the best of our knowledge, been paid to analysis of USD/CNH options. We also use this information to analyze USD/CNH market sentiment and uncertainty. In section 4, we explore the forecasting performance of the option-implied PDFs. Section 5 concludes, providing suggestions for future research. Additional robustness tests included in the appendix.

2 The analytics of option-implied FX probability density functions

Recently developed techniques to uncover information on market expectations implicit in over-the-counter option prices make it possible to construct forward-looking implied risk-neutral and real-world probability density functions from USD/CNH option prices. These risk-neutral and real-world USD/CNH densities contain information on the probability-weighted expectations of market participants as to USD/CNH price at option expiration dates. By tracking these densities over time, it is possible to observe the evolution of market exchange-rate expectations. Notably, the approach makes no other distributional assumptions than allowing for skewness and jumps in the CNH exchange rate. Given that currencies crash from time to time, this is an important feature (see e.g. Farhi and Gabaix, 2016).

The literature on estimation of risk-neutral densities (RNDs) covers a wide range of techniques including parametric, non-parametric, and structural models. Here, we employ the method of Malz (1996, 1997a, 1997b, 2014) to derive parametric RNDs. The volatility smile interpolation method is analytically tractable since it requires only three observations to uncover the underlying

[4] Hong Kong's CNH options market has expanded exponentially. The average daily turnover of CNH options has increased from USD 0.03 billion in 2010 to USD 18 billion in 2016.
For more, see https://www.hkex.com.hk/eng/prod/drprod/rmb/Documents/USDCNH_Opt_Jan17_E.pdf.

density. Other techniques of this class include those derived by Shimko (1993) and Bliss and Panigirtzoglou (2000). Informative discussions regarding various RND methods are provided by Campa et al. (1998), Jondeau and Rockinger (2000), Lynch and Panigirtzoglou (2004), and Bliss and Panigirtzoglou (2004).[5]

Real-world densities (RWDs) can be recovered from RNDs by making assumptions about risk preferences.[6] Jackwerth (2000) observes that the *risk-neutral probability is equal to the real-world probability times a risk-aversion adjustment*. Essentially, RWDs are a by-product of the benchmark RNDs and the degree of risk aversion. In practical terms, this means that RWDs can be derived by considering specific utility functions to describe risk preferences. Bliss and Panigirtzoglou (2004), employing the constant relative risk aversion (CRRA) utility function, provide the following example. Under the assumption of risk-neutrality, the fair price of a European call option is given by its discounted expected value

$$c(t,X,T) = e^{-r\tau}\int_0^{+\infty}(S_T - X)\pi_t^\tau(S_T)dS_T, \tag{1}$$

where $c(t,X,T)$ is the observed market price of the call option at time t, with exercise price X and the market value of the exchange rate at the expiration date T, given by S_T.[7] The time to maturity, $\tau = T - t$, is the difference between the expiration date T and the observation date t. The domestic risk-free interest rate is given by r and the time t expected risk-neutral PDF of the exchange rate τ months in the future is denoted by $\pi_t^\tau(x)$. Mathematically speaking, we can derive $\pi_t^\tau(x)$ from equation (1) by taking its second derivative with respect to the strike price

$$\frac{\partial^2 c(t,X,T)}{\partial X^2} = e^{-r\tau}\pi_t^\tau(X)\,, \tag{2}$$

[5] The approaches appear different, but their underlying concept is quite similar. Parsimony and tractability are leading reasons in why these modeling approaches have gained popularity.

[6] There is no reason to expect that real-world and risk-neutral expectations should be identical. On the contrary, the financial economics literature documents that time-varying risk premia are pervasive (see e.g. Della Corte et al., 2016). Moreover, the literature on RNDs vs. RWDs is unsettled. With no consensus on which technique is best, the relevance of reverse-engineered RNDs or RWDs remains controversial. Cochrane (2017, p. 967) underscores this in his excellent macro-finance overview: "… it would be entirely sensible for people to think about and report risk-neutral probabilities, not true probabilities. … Risk-neutral probabilities are a good sufficient statistic to make decisions." Our reverse-engineered RWDs are presented in the appendix.

[7] See Breeden and Litzenberger (1978). A *European call option* gives the buyer the right to buy, on a specified date, the underlying asset (in our case the USD/CNH spot exchange rate) at a certain price. A *put option* gives the buyer the right to sell the underlying asset at a certain price.

and pre-multiplying (2) with the inverse of the discount factor $e^{-r\tau}$. To derive the PDF from equation (2) one would need continuum of strike prices, which is rarely the case in reality. The method of Malz (1997a, 1997b) overcomes this obstacle by making use of the pricing conventions of over-the-counter (OTC) currency options. The quotation of OTC currency options is done in terms of Black-Scholes (BS) implied volatilities and the moneyness represented by the option delta. In other words, implied volatility is the volatility backed out from an option contract on the price of the underlying asset. Investors are assumed to be risk-neutral and risk consists only of “known unknowns.”[8]

Building upon the Garman and Kohlagen (1983) formula the call option delta, which measures the distance between the strike price and the actual market price is given by

$$\delta_c(S_t, \tau, X, \sigma_t, r_t, r_t^*) \equiv \frac{\partial C_{BS}}{\partial S_t} = e^{r_t^* \tau} \Phi \left[\frac{\ln\left(\frac{S_t}{X}\right) + \left(r_t - r_t^* + \frac{\sigma_t}{2}\right)\tau}{\sigma_t \sqrt{\tau}} \right] \in (0,1), \tag{3}$$

where r_t^* stands for the foreign risk-free interest rate and σ_t for the implied volatility. A call option that is at-the-money (ATM) would have a delta of 50 percent. An out-of-the-money call option would have a delta of less than 50 percent and an in-the-money call option a delta above 50 percent. Put-call parity implies that the call delta equals one minus the put delta. Hence, the moneyness of both types of options can be expressed by (3).

Although markets are well aware that the assumptions of the BS model are violated in reality, the BS formula is still widely used as a metric to convert between prices in terms of currency and implied volatilities. The crucial assumption of the BS model is that the log-normality of the underlying forward-looking distribution, i.e. the exchange rate at maturity, follows a geometric Brownian motion with constant volatility. Since distributions of financial assets are known to be often asymmetric and heavy-tailed, the log-normality assumption no longer holds, implying a non-constant σ_t for different values of delta.

Volatilities for FX options with different times to maturity also differ from each other, leading to a term structure of volatilities. This well-known phenomenon is called the *volatility smile*, because a call (put) option implied volatility tends to increase for delta values smaller (larger) than

[8] Implied volatility is a measure of the variability of the exchange rate. Unlike realized volatility, it is forward-looking and reflects the risk regarding the future exchange rate. Giordani and Soderlind (2003) show that risk can be decomposed into two elements, one related to volatility and a second related to disagreement. Other studies, such as Anderson et al. (2009), relate the former to risk (known unknowns) and latter to uncertainty (unknown unknowns).

50 percent. Thus, the shape of the volatility smile and the shape of the underlying PDF are closely related to each other. The smile can be thought of as a U-shaped function, $\sigma_t(\delta)$, with the minimum approximately at $\delta = 0.5$. An asymmetric smile would translate into a skewed PDF, while a smile with a higher curvature would translate into a heavy-tailed PDF.

The indirect method of Malz (1997a, 1997b) uses these properties of the volatility smile to derive the PDF. A major advantage of this method is that it requires only three observations to uncover the underlying density. It is based on the idea of fitting a volatility smile of implied volatility and the delta space. The starting point is a quadratic approximation of the $\sigma_t(\delta)$ function given by

$$\sigma_{25\delta,t}(\delta) = b_0 atm_t + b_1 rr_{25\delta,t}(\delta - 0.5) + b_2 bf_{25\delta,t}(\delta - 0.5)^2 \quad (4)$$

Level, symmetry, and curvature of (4) are determined by three option bundles mainly traded in OTC markets, which are constructed by ATM and OTM put and call options, where moneyness is set equal to 25 percent in terms of the delta. This delta reflects the fact that the 25% market is the most liquid.[9] The bundles are the ATM straddle (atm_t), the 25δ risk reversal ($rr_{25\delta,t}$), and the 25δ butterfly ($bf_{25\delta,t}$).

A *ATM straddle* is a set of call option and put option with the same strike price. The quote corresponds to a strike price where the Garman and Kohlhagen (1983) delta of the straddle equals zero.

The *25δ risk reversal* measures the difference in implied volatilities between an out-of-the-money call option and an out-of-the-money put option. Option traders use risk reversal quotes to quantify the asymmetry of the implied volatility smile, reflecting the skewness of the risk-neutral currency return distribution.

The *25δ Butterfly spreads* are defined as the average difference between out-of-the-money implied volatilities and the delta-neutral straddle implied volatility.

Mathematically, these bundles are calculated as follows:

$$atm_t = \sigma_{50\delta c,t} + \sigma_{50\delta p,t} \quad (5)$$

$$rr_{25\delta,t} = \sigma_{25\delta c,t} - \sigma_{25\delta p,t} \quad (6)$$

$$bf_{25\delta,t} = \frac{\sigma_{25\delta c,t} + \sigma_{25\delta p,t}}{2} - atm_t. \quad (7)$$

[9] The 10% and 35% delta markets are less liquid.

In equations (5) and (6), positive risk reversal means that 25δ calls are more expensive than 25δ puts. This implies that the market expects the USD to appreciate against the CNY within the next τ months, which further implies that the underlying PDF skews to the right.

Similarly, equation (5) implies that a larger butterfly increases the curvature of the smile. This indicates that both OTM call and put options get more expensive than ATM options and that the market sees a greater possibility for large moves in both directions. The result would be a heavy-tailed underlying PDF.

Finally, ceteris paribus, a larger value for the ATM straddle indicates that the level of the volatility smile increases, thereby raising the price of ATM options relative to OTM options. Since the ATM straddle only pays out when the exchange rate moves into either direction, this directly translates into a distribution with a larger standard deviation.

Equation (3) to (7) can be used to back out (b_0, b_1, b_2) = (1,-2,16), because, by construction, $atm_t = 0.5$. As mentioned in calculating the derivative given in (2), a *continuum* of strike prices is needed. For this, we have a volatility smile for each day given by (4) and (b_0, b_1, b_2) = (1,-2,16) and the delta function (3). This gives the resulting system of equations:

$$\sigma_{25\delta,t} = atm_t - 2rr_{25\delta,t}(\delta - 0.5) + 16bf_{25\delta,t}(\delta - 0.5)^2 \tag{8}$$

$$\delta = e^{r_t^* \tau}\,\Phi\left[\frac{\ln\left(\frac{S_t}{X}\right) + \left(r_t - r_t^* + \frac{\sigma_{25\delta,t}}{2}\right)\tau}{\sigma_{25\delta,t}\sqrt{\tau}}\right], \tag{9}$$

where the only unknown is the strike price X and which can be solved numerically to get the function $\sigma_{25\delta,t}(X)$. Inserting $\sigma_{25\delta,t}(X)$ into the BS formula for given τ and t yields the call price as a function of a continuum of strike prices $c(t, X, \tau) \equiv c(X)$. The derivative can then be approximated by the second-order centralized difference quotient for given step size h

$$\frac{\partial^2 c(X)}{\partial X^2} \approx \frac{c(X+h) + c(X-h) - 2c(X)}{h^2}. \tag{10}$$

Besides option data, we gather data on the spot USD/CNH and USD/CNY exchange rates, the USD/CNH one-month to one-year forward exchange rate, and the USD/CNY daily fixing. The interest rate is the CNH HIBOR rate with one-month to one-year maturity. The options are traded on the Hong Kong Exchanges and Clearing Limited (HKEX). All data are from Bloomberg.[10] Prior to estimation, we carefully check all data for errors and omitted observations.

3 Empirical results

The results are reported by plotting the RNDs estimated using the Malz method described above for various maturities at selected dates.

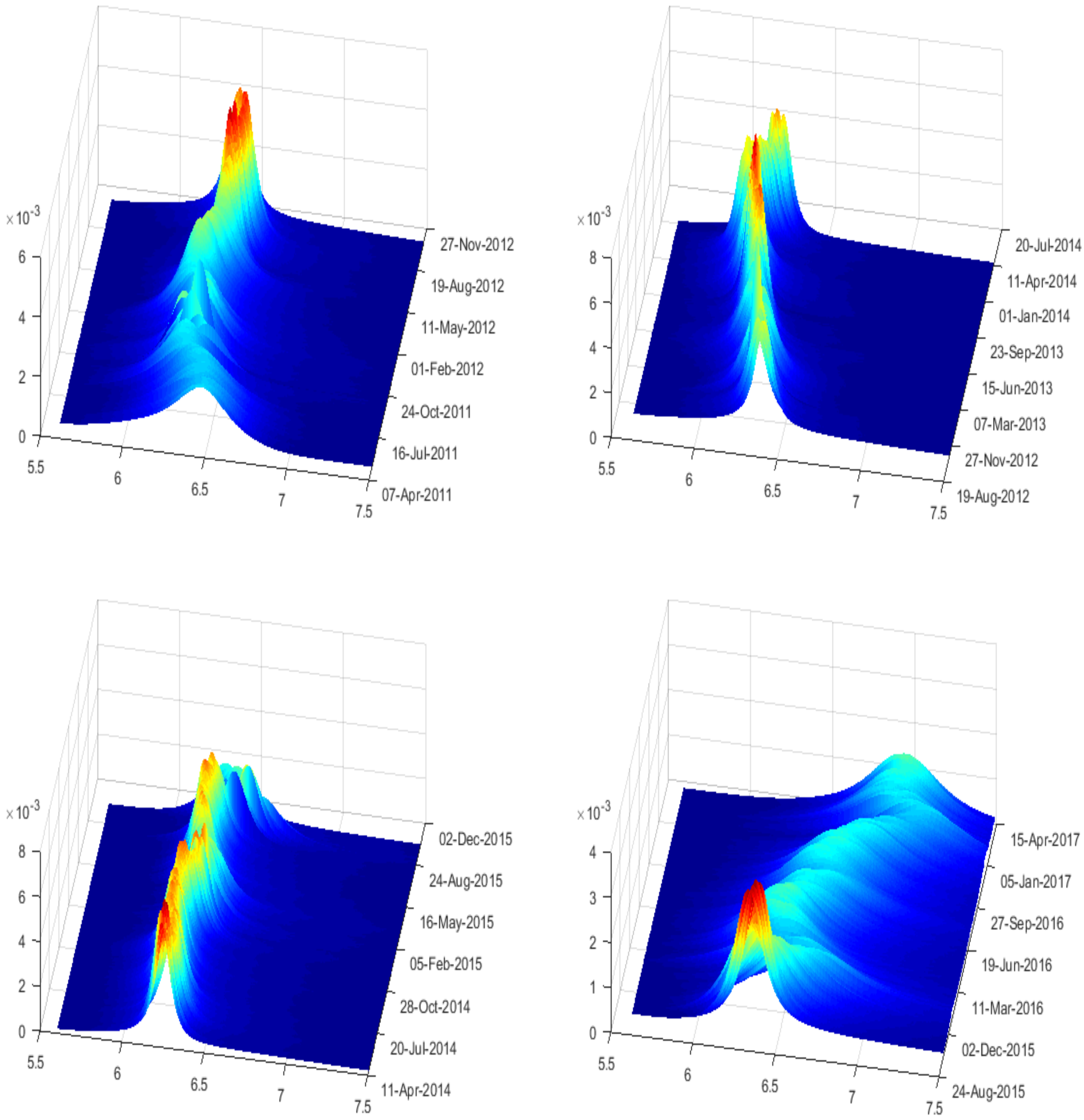
Figure 1 provides a three-dimensional presentation of the 1,540 12-months-ahead RNDs for our overall sample period (9 May 2011 – 31 March 2017). To enhance the clarity of presentation, the total sample period is partitioned into four subperiods.

Figure 2 presents exemplary two-dimensional RNDs for various maturities and selected dates. The figures reveal that the shapes of the distributions vary considerably over time and across maturities with regard to width and symmetry of the functions. Thus, the initial graphic explication of RNDs already provides tantalizing information about changes in market participant perceptions of future exchange rate movements.[11]

[10] We employ the MATLAB code provided by the Bank of England (2015) to solve system (8) and (9) for $\sigma_{25\delta,t}$. We have revised the code to be able to calculate the difference quotient of equation (10) for various step sizes.

[11] The time-varying FX densities are analogous to kaleidoscope patterns produced by refracted jumbles of colored glass. The densities represent the pattern of prices that are determined by demand and supply in the FX options market. The passage of time is necessarily marked by the discovery of new information. This shakes the kaleidoscope and a new probability density function of expected exchange rates emerges.

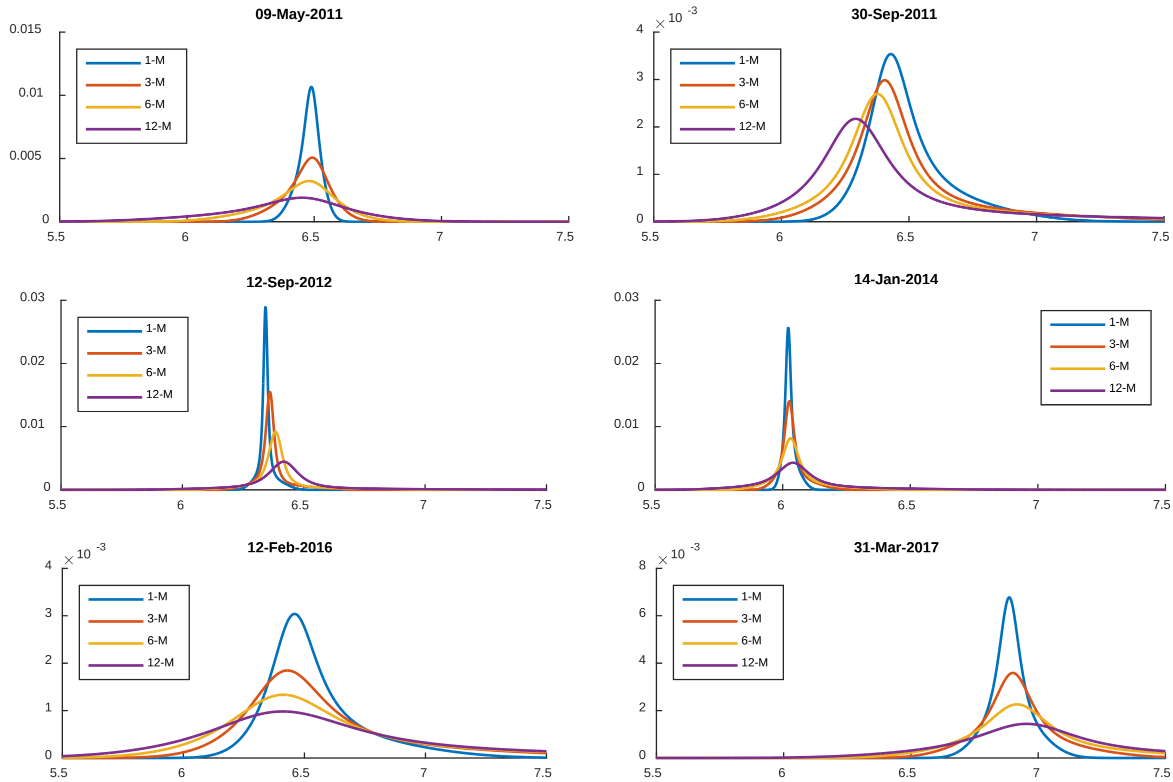
Figure 1 3-D graph of 12-months-ahead RNDs (9 May 2011 – 31 March 2017)



While the movements in the entire distribution function provide interesting snapshots of daily changes in exchange rate expectations, gauging information about systematic impacts on the expectations requires the use of time-varying implied moments: mean, standard deviation, skewness, and excess kurtosis. The *mean* is the point forecast of the USD/CNH exchange rate for the respective maturity. The *standard deviation* of the RNDs is a measure of uncertainty, or risk aversion, associated with the USD/CNH currency. *Implied skewness*, a measure of asymmetry of the estimated

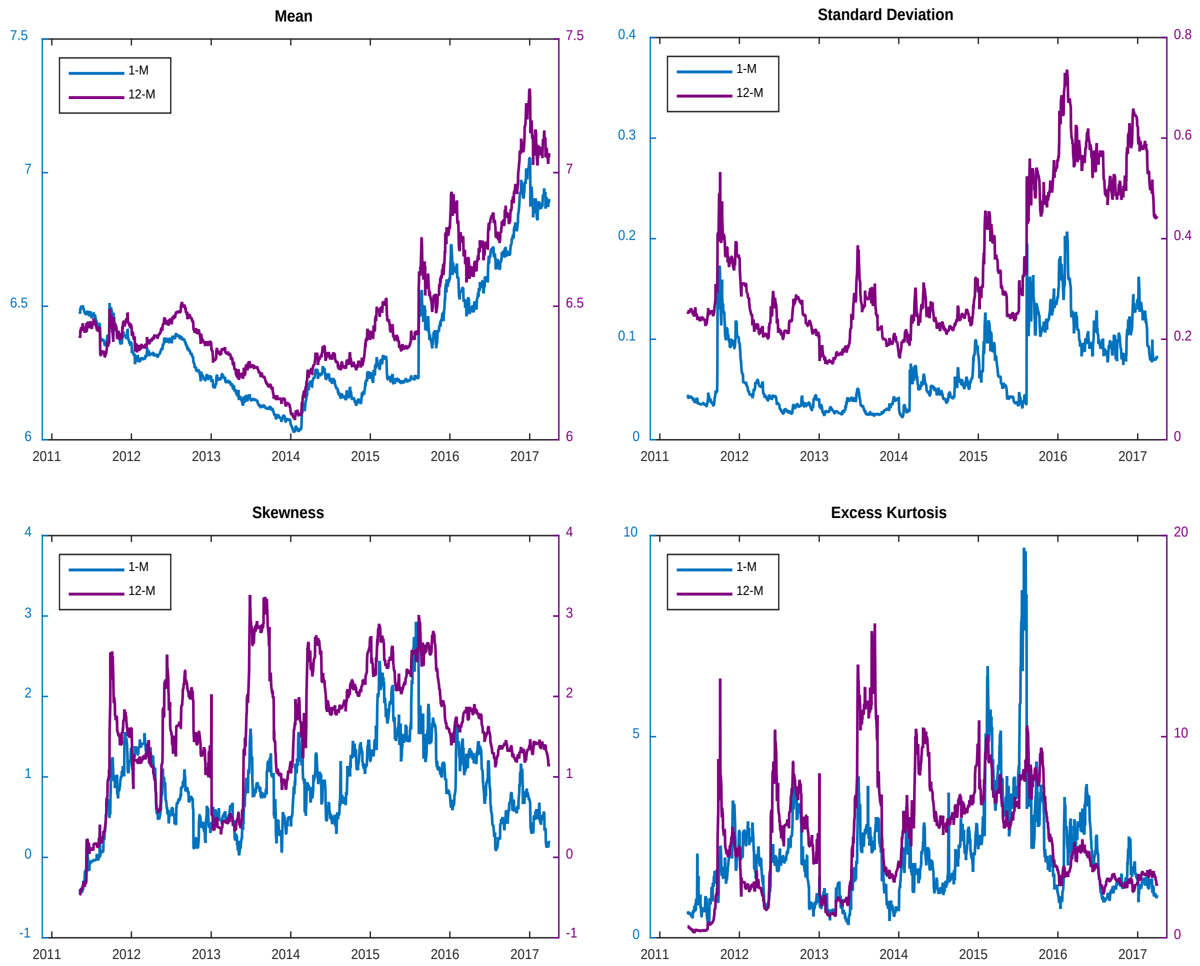
RNDs, provides useful information in that it is a measure of the direction of the market's view regarding future exchange rate movements. The asymmetry informs market participants about the balance of risks. Positive skewness is consistent with investors expecting more negative than positive surprises regarding the USD/CNH exchange rate. Large changes in implied skewness may indicate that the market's assessment on the probability of future CNH appreciation or depreciation has changed. *Implied kurtosis* provides a measure of the market's assessment of the likelihood of extreme events by measuring the length of the tails of the RND function. In all cases, the kurtosis data show fatter tails than the normal distribution. The day-to-day time series from 9 May 2011 to 31 March 2017 (1,540 observations) for the 1-month- and 12-months-ahead implied moments, together with the respective forward rates, are plotted in Figure 3.[12] Figures 2 and 3 highlight the fact that RNDs provide a far more detailed picture of the underlying market expectations than the simple forward rate.

Figure 2 RNDs for selected dates and maturities



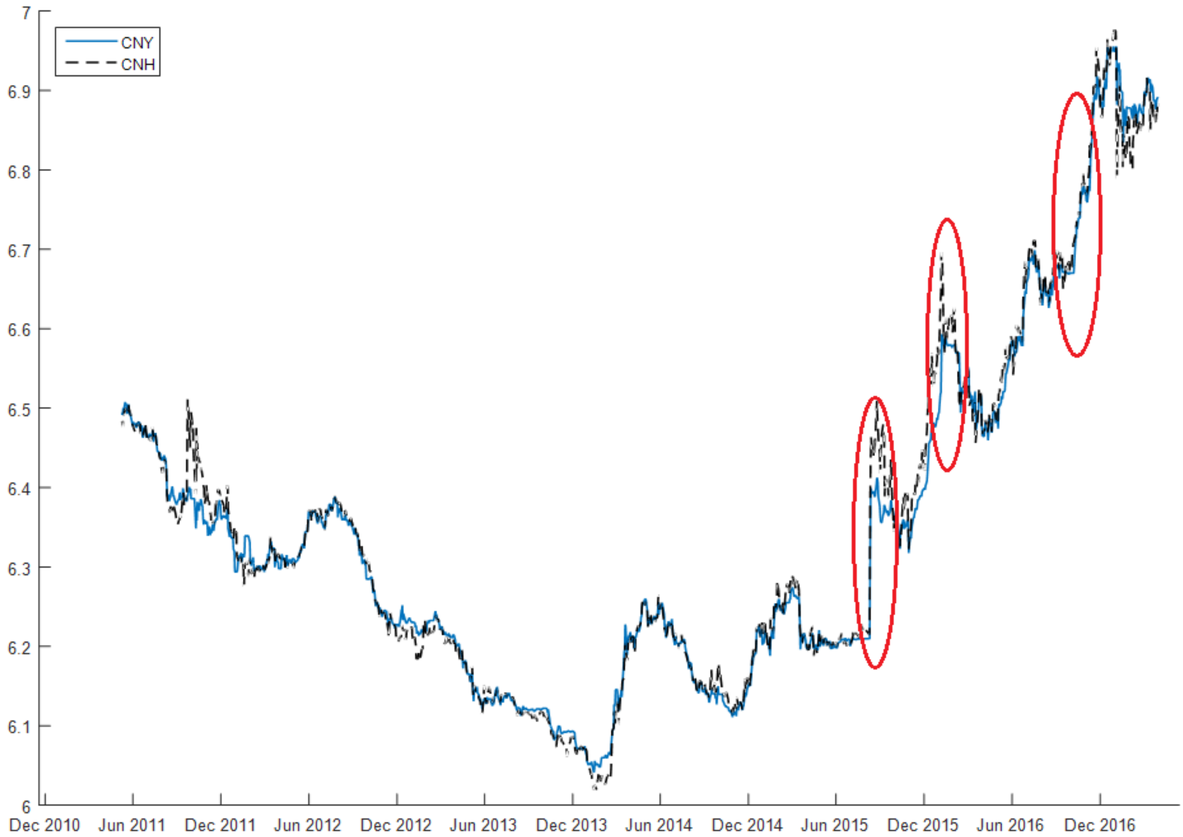
[12] The graphs for the in-between (3-months- and 6-months-ahead) moments are available on request.

Figure 3 1- and 12-months-ahead moments of the RNDs



We next present several in-depth event studies. In these case studies, a special focus will be placed on three turmoil subperiods highlighted in Figure 4 with red frames. This provides more granular insights.

Figure 4 USD/CNH and USD/CNY FX rates (9 May 2011 – 31 March 2017)



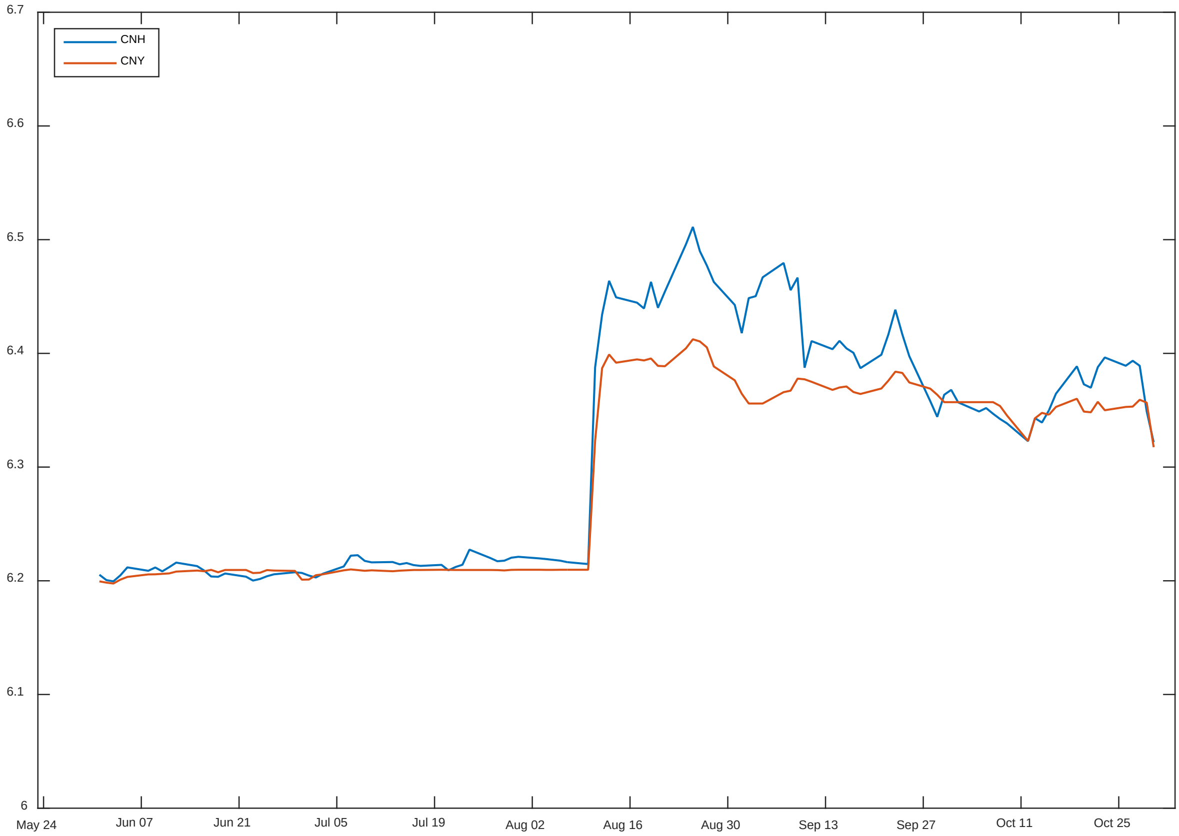
The August 2015 devaluation

First, we zoom in on the CNH dynamics of August 2015. Figure 5 provides a step-by-step evaluation of the densities from July to September 2015. As expected, probabilities constantly change in the world of human interaction. Figure 5 shows the PBoC surprised the markets on 11 August with its 2.75 percent devaluation of the CNY against the USD. A day later, the central bank sent further shockwaves with a second devaluation, pushing down the price by another 0.72 percent against the USD. On the third trading day, the offshore CNH fell again, reaching 6.46 to the USD. Over the three days, the offshore CNH exchange rate depreciated by 4.01 percent against the USD. Global markets were rattled by fears that the RMB drop might induce a devaluation spiral.

The offshore CNH exchange rate depreciated more sharply than the onshore exchange rate. While the depreciation was relatively modest, it commanded serious attention as the first devaluation of the Chinese currency since 1994. Following the August devaluation, the gap between the

CNH and the CNY continued to widen until October 2015.[13] Asian financial markets experienced secondary effects such as falling stock prices and weaker currencies.

Figure 5 USD/CNH and USD/CNY exchange rate (1 June 2015 – 31 October 2015)



The CNH densities for various maturities in Figure 6 suggest that the devaluation was an unforeseen event.

[13] While the PBoC initially gave the markets greater say in the CNY's value, it backtracked and intervened to stem the ensuing decline. A timeline of China's interventions to keep the CNY stable after the August devaluation is available at http://www.reuters.com/article/us-china-yuan-interventions-factbox-idUSKCN0RI0NJ20150918.

Figure 6 USD/CNH option-implied densities (15 July – 30 September 2015)

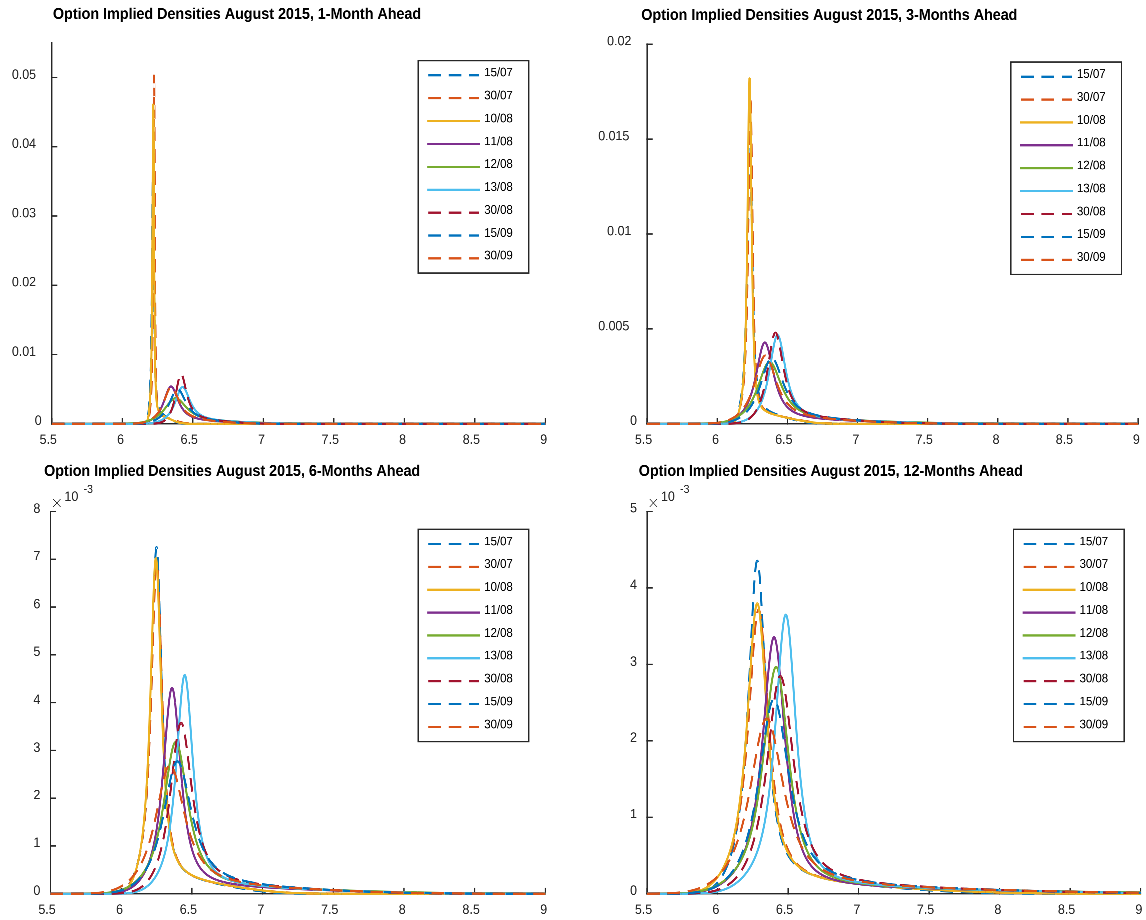
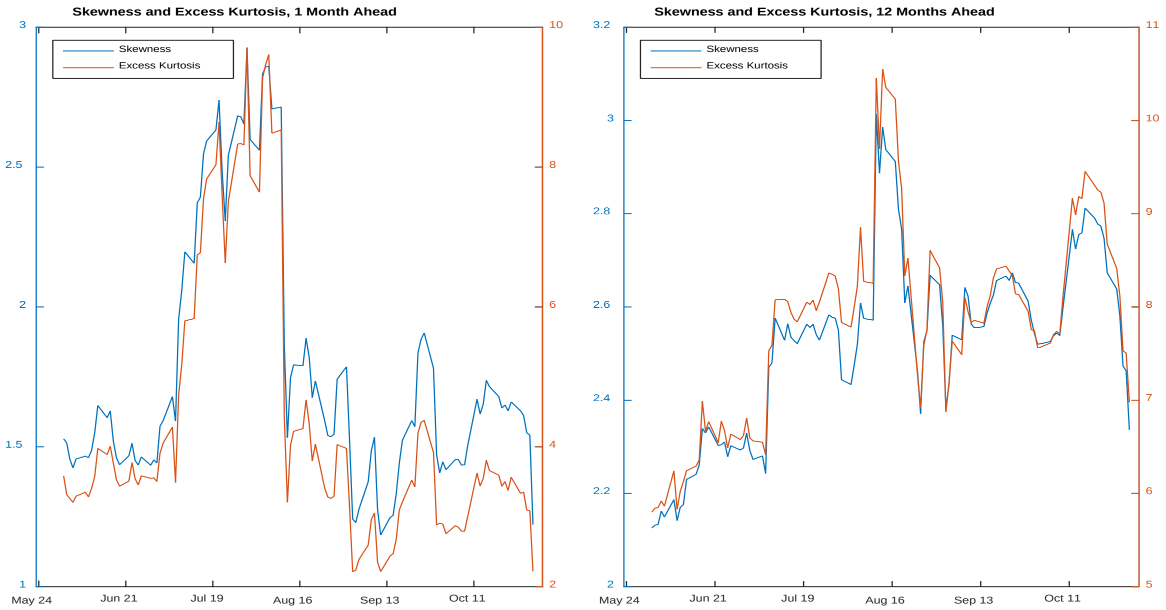


Figure 7 shows the skewness and the excess kurtosis calculated from option prices for the June-to-October period of interest. When risk-neutral density has a positive skewness, the probability mass shifts toward the right tail. This indicates a higher probability of depreciation than appreciation of the CNH against the USD. Excess kurtosis measures market expectations of extreme changes in the USD/CNH exchange rate. The higher the excess kurtosis, the higher the probability concentrated in the tails of the distribution.

Figure 7 Skewness and excess-kurtosis coefficients (1 June – 31 October 2015)



The higher moments in Figure 7 provide interesting insights. In particular, the 1-month-ahead skewness and excess kurtosis indicate that the depreciation was not entirely unexpected. Both higher moments increase significantly in early July 2015, reflecting a change in the market assessment.[14] A sequence of released data shows failure of efforts to boost exports and growth against the headwind of an overvalued currency.[15]

While it is clear the PBoC measures triggered fears that the Chinese economy was in worse shape than believed, investors were not explicit as whether they though the CNH losses represented short-run fluctuations or the start of a long-term depreciation trend. The 12-months-ahead densities in Figure 7 and the normalization of both higher moments after 14 August in Figure 7 imply that investors regarded the depreciation as a one-time fix and not a signal that China was embarking on a long-term devaluation of the exchange rate. As investors saw the correction as short-lived, they impliedly expected the Chinese economy to rebound.

[14] This is a good example of the power of these methods in extracting information from options prices. The higher moments of the distributions often move around times of turning points, suggesting that the options market may anticipate impending trend reversals.
[15] The daily BIS nominal effective exchange rate index for the CNY dropped to 124.14 on 25 August 2015, down 4.01% from a record high of 129.32 on 6 August 2015 (see http://www.bis.org/statistics/eer.htm).

The January 2016 stock market panic

Our next close-up involves the eventful weeks on the cusp of 2015 and early 2016. On 4 January, the first trading day of 2016, the CSI 300, an index of the country's biggest stocks, fell by 7 percent, the worst-ever start to a year for Chinese markets. The share price plunge followed weak data from China, and triggered an early closure of the Shanghai and Shenzhen stock markets under the just-introduced "circuit breaker" mechanism. Stock markets around the world followed suit. On 7 January, trading on Chinese stock markets was again halted after barely 30 minutes of trading, when panic selling and an attempt to beat the circuit breaker saw shares again fall by 7 percent.[16]

Figure 8 indicates that it was a rocky start to the new year in the onshore and offshore RMB markets. Thereby, the depreciation on the offshore market was more pronounced than on the onshore market. The PBoC intervened in the offshore market over several days to stabilize the falling offshore RMB by selling USD/CNH.[17] The tightening of CNH funding caused many investors to unwind their positions. It all started with the CNY's decline in the first week of the year. On 4 January, the PBoC set the daily USD/CNY fixing at 6.5032, the weakest since May 2011. Bets that the Chinese authorities would further depreciate the CNY increased over the following trading days. The pace of the PBoC's downward FX guidance encouraged traders to boost selling of the CNH. This widened the spread between the CNY and the more market-sensitive CNH to 1,405 pips – its widest point ever.

On 12 January, the overnight CNH HIBOR soared to 66.8 percent. The one-week rate jumped to an unprecedented 33.8 percent. A week later the PBoC issued a regulation mandating all foreign institutions to hold reserves on offshore RMB deposits at the prevailing reserve rate requirement between 15 and 17.5 percent with retroactive effect.[18] Both measures led many international institutions to scale back their RMB business. Higher interest rates curbed short selling substantially and eased the downward pressure on the CNH. By 13 January, the CNH had recaptured the ground lost over the past week and the offshore-onshore spread narrowed to 90 pips. For our purposes, it is notable that the wide CNH-CNY spread was transient. Over time, the spread has been quite narrow.

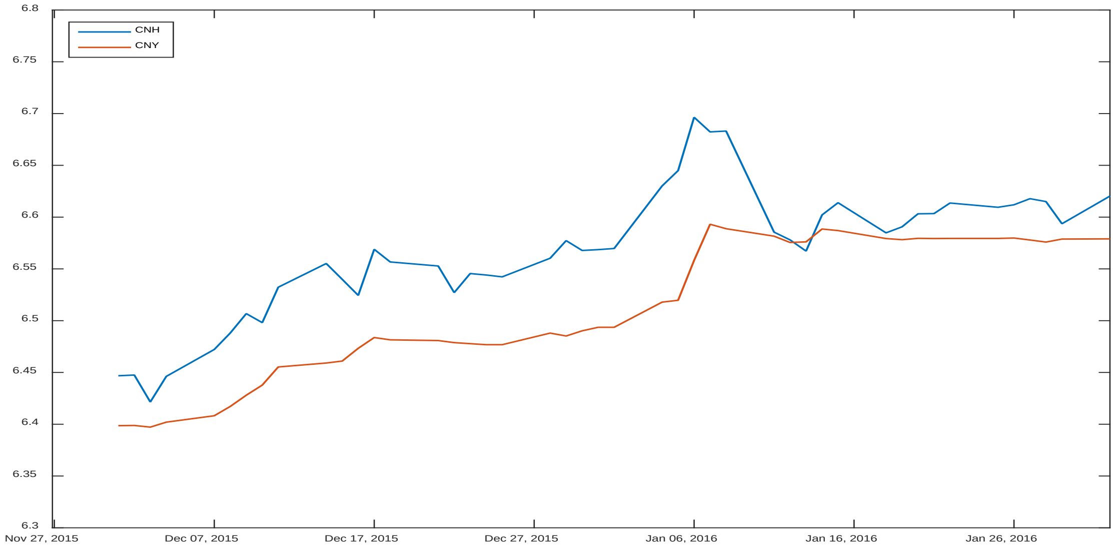
[16] Ironically, the "circuit breaker," the mechanism meant to prevent extreme volatility, seems to have made things worse. Market participants rushed to sell shares on fears of being locked out when the automatic trading shut-down kicked in. The Chinese authorities later scrapped the mechanism.

[17] The trigger may have been the widening spread between the onshore and offshore rates. It is worth recalling that the convergence between the two exchange rates was a cardinal criterion during the run-up to the IMF SDR decision.

[18] PBoc Press Release "PBC Normalizes Deposit Reserve Requirements on Offshore Financial Instituions". Available at http://www.pbc.gov.cn/english/130721/3005730/index.html.

During the liquidity crunch, the nine banks designated as Primary Liquidity Providers drew additional RMB liquidity from the HKMA under its RMB liquidity facilities.[19]

Figure 8 USD/CNH and USD/CNY exchange rates (1 December 2015 – 1 February 2016)



How much of this turmoil reflects rule changes and other policies at the Chinese stock market, and how much was based on broader economic fundamentals that might have a further impact on China's future growth? Although the combination of weak Chinese economic data, headline risk, and attractive external investment opportunities could have led to the view that the weaker CNH could continue, the densities in Figure 9 clearly indicate that the CNH devaluation at the beginning of January did not de-anchor the CNH exchange rate. Instead, the CNH was expected to lean towards 6.7 against the USD. This is quite visible when comparing the densities for various maturities. Concurrently, the right tails of the RND functions also got much fatter indicating the rising uncertainty in the market sentiment and the perceived increase in the probability of a further depreciation.

The key takeaway from Figure 9 is the long-run sustained downside risk for the USD/CNH. This is also visible in the higher moments in Figure 10. The increasing skewness, particularly in late January just ahead of the Chinese New Year, suggests that the market feared CNH depreciation and was willing to pay more for cover. The resulted in a foreseeable tightening of liquidity in the CNH market increased concerns over rising intermittent volatility.

[19] See *Financial Times* (2016), "Renminbi Borrowing Rate plunges in Hong Kong," 13 January 2016.

Figure 9 USD/CNH option-implied densities (31 December 2015– 29 January 2016)

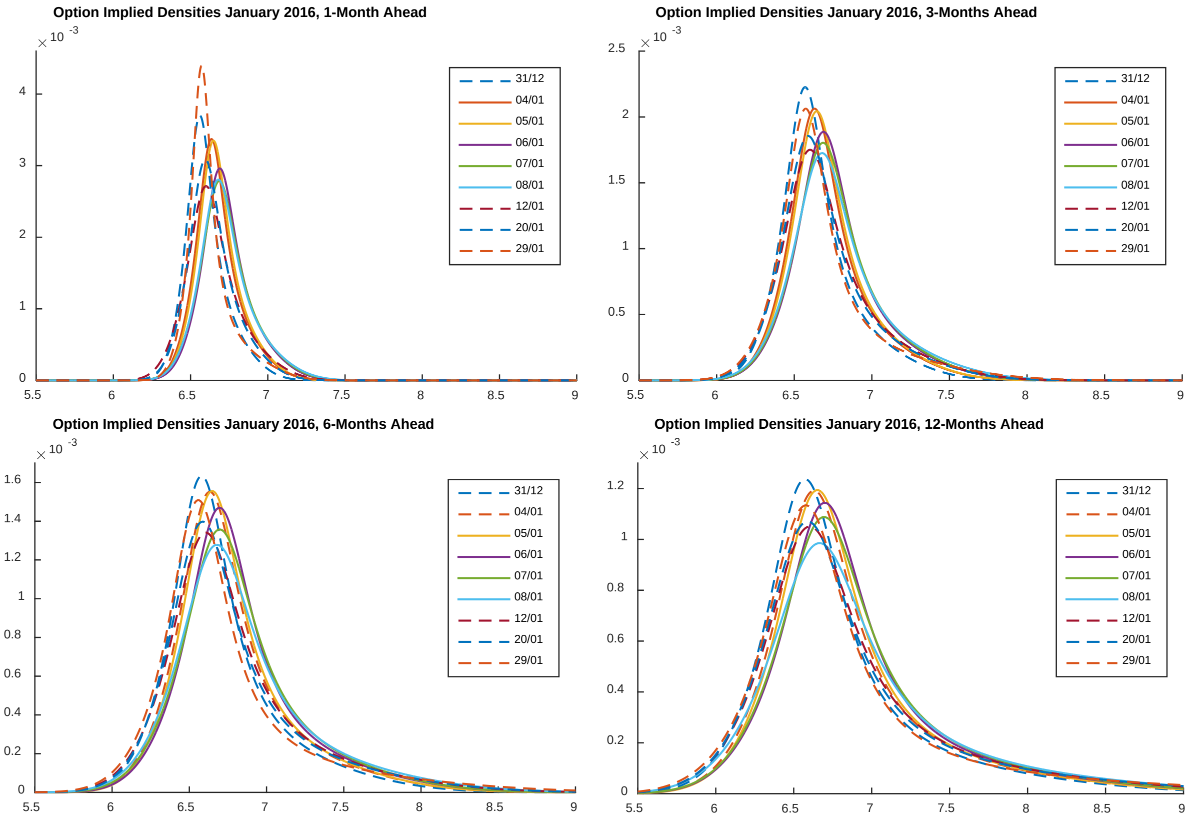
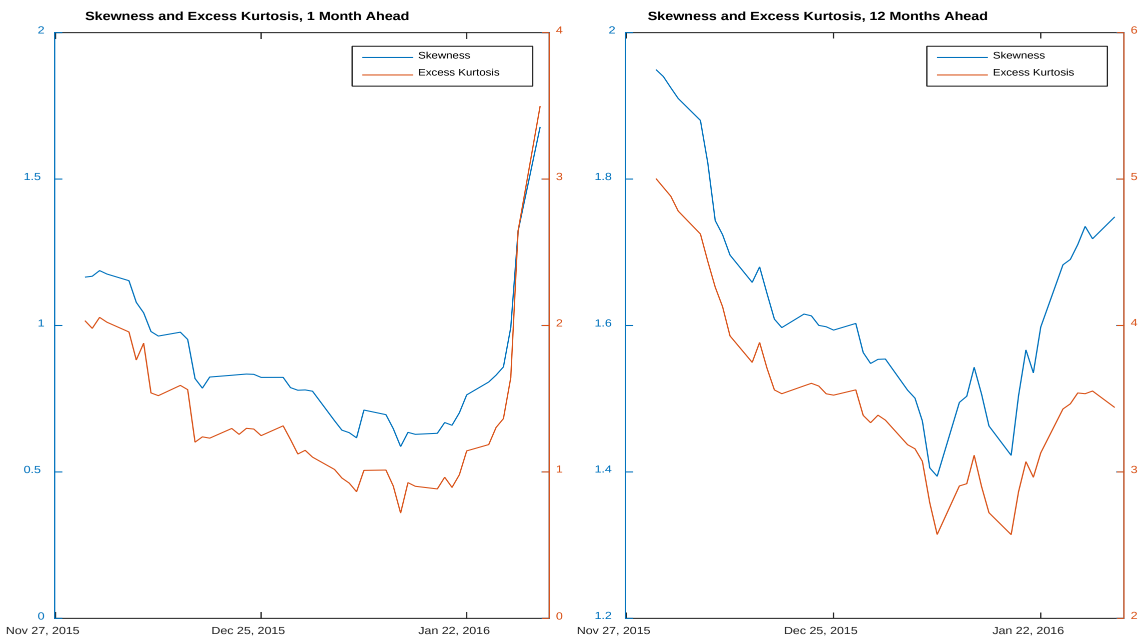


Figure 10 Skewness and excess kurtosis coefficients, 1 December 2015 – 01 February 2016



IMF including RMB in the SDR basket & Trump's election victory in the US

Finally, we dig a bit deeper into the role of two important events at the end of 2016. Effective October 1, the IMF added the RMB to the basket of currencies that make up its Special Drawing Right (SDR) asset. The RMB joined the US dollar, euro, yen, and British pound in as the SDR basket's fifth currency. It was the first emerging market currency to ever be included in the IMF's SDR basket.

The inclusion to the SDR basket is an important milestone in the integration of the Chinese economy into the global financial system and signals that the RMB is on course to becoming a major reserve currency.

When comparing the RNDs before and after the SDR inclusion in Figure 12, we see that there is no noticeable change in the expected exchange rate after of the IMF announced its decision on September 30. The is a slight increase in volatility, which may signal investor anxiety. Beyond the limited increase in the second moment, however, no other mood changes are visible. For example, the small and stable CNH vs. CNY currency spread in Figure 11 indicates a comparatively hassle-free period. It may be that the IMF decision was anticipated and priced in by the financial markets, or that the move was classified as a technical issue of largely symbolic significance. While the exchange rate of the CNH did not move perceptibly on the event day, the CNH and the CNY weakened after Chinese markets resumed trading after the National Day holidays.

The situation in November 2016 is markedly different. The CNH experienced a new round of depreciation pressure against the USD after having blown through what had been considered a resistance point at the level of 6.7 to the USD in October. Furthermore, in the wake of Donald Trump's surprise victory in the presidential US election on 8 November 2016 and the Republicans retaining control of both houses of Congress, the offshore rate weakened in tandem with the CNY, with the PBoC gradually lowering the midpoint around which the CNY was allowed to trade. On 2 January 2017, the CNH fell to a new all-time low against the USD of 6.9895. During the electoral campaign, Trump and his surrogates had accused China of manipulating its currency to gain an unfair advantage for its exports.[20]

[20] The US trade and customs enforcement law enacted in 2016 sets out three criteria for identifying manipulation among major trading partners: a material global current account surplus in excess of 3% of GDP, a significant bilateral trade surplus with the US of at least USD 20 billion, and persistent one-way intervention in foreign exchange markets in excess of 2% of GDP over the preceding 12 months. China only meets one of these criteria – a large trade surplus with the US. The RMB is currently close to the value that would be implied by fundamentals. For the latest fundamental equilibrium exchange rate (FEER) estimates see https://piie.com/publications/policy-briefs/estimates-fundamental-equilibrium-exchange-rates-november-2016.

Figure 11 USD/CNH and USD/CNY FX rates (LHS) and CFETS Index (RHS, in reverse scale, 1 September 2016 – 30 November 2016).

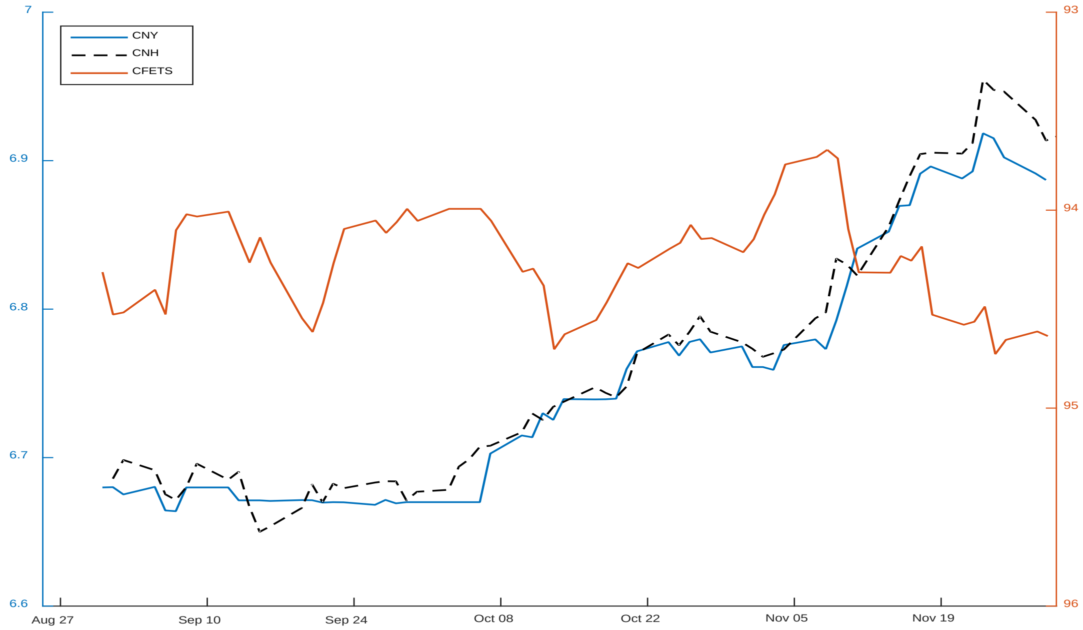


Figure 12 USD/CNH Option Implied Densities (29 September 2016 – 5 October 2016)

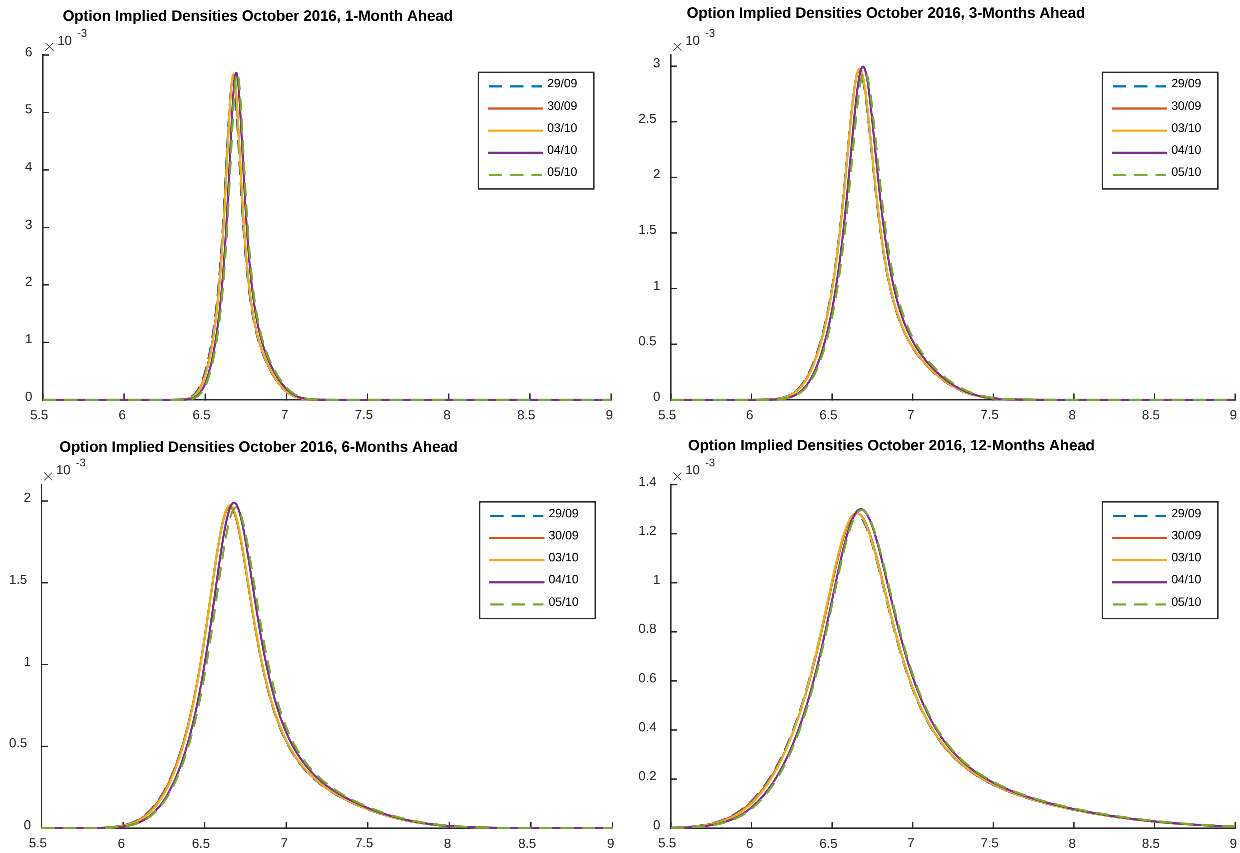


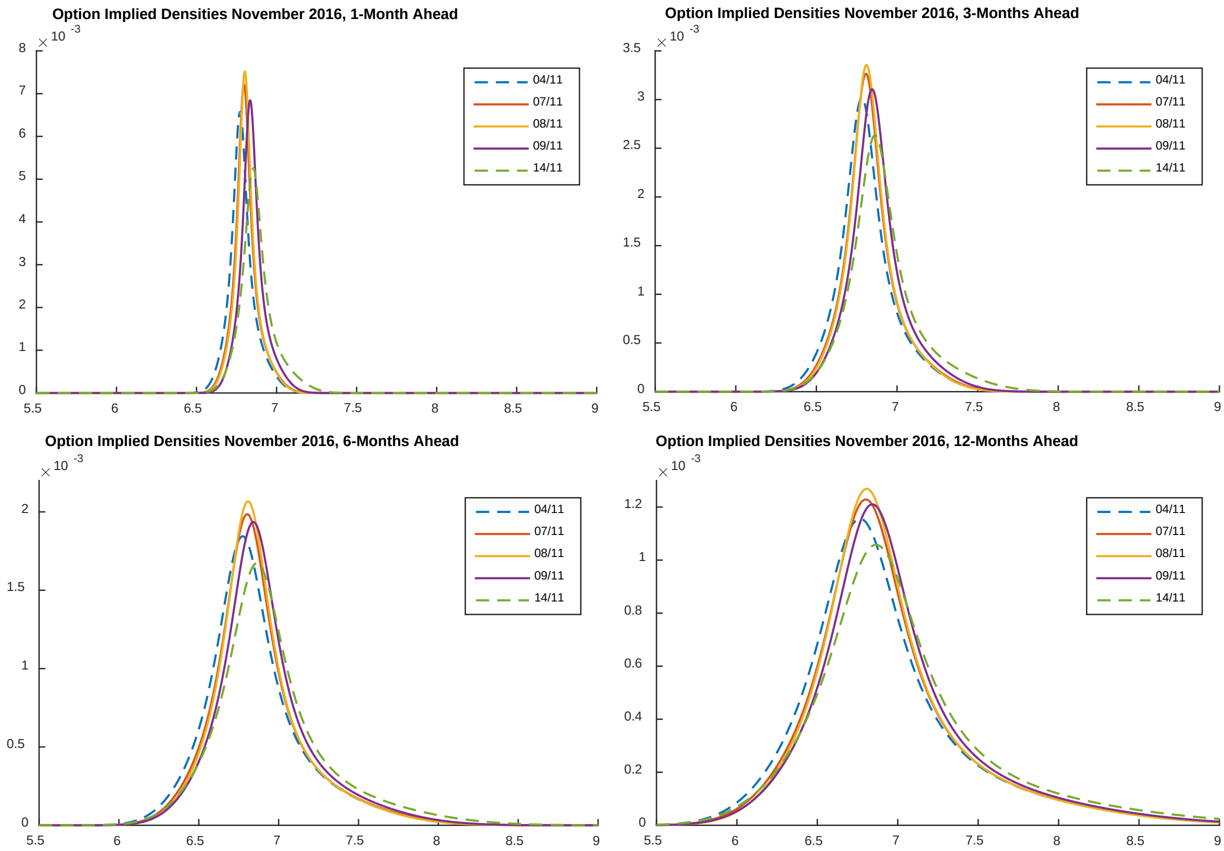
Figure 13 indicates that the media coverage, aggravated by tighter Chinese capital controls, lingering PBoC intervention worries, and persistent depreciation expectations, kept CNH investors cautious. These concerns coincided with market jitters about the Fed's unwinding from quatitative easing. The sensitivity of emerging market economies to changes in Fed policy was amply illustrated by the "taper tantrum" of 2013, when the announcement that it would slow and eventually stop the purchases of government bonds led to turmoil in emerging markets.

Notably, China had moved ahead on 11 December 2015 with reform in its exchange-rate regime by introducing the China Foreign Exchange Trading System (CFETS) exchange-rate index, which measures the RMB's strength relative to a basket of 13 trade-weighted foreign currencies. In other words, the PBoC benchmarked its exchange rate policy from a stable USD/CNY to a stable CNY against the CFETS basket. Weights for the different currencies were provided as part of the announcement.[21]

The move to a multilateral exchange-rate target put the RMB firmly on the road to a more flexible exchange-rate regime. Comparison of the effective CFETS exchange-rate index and the two bilateral RMB exchange rates in Figure 11 reveals an opposite movement of the multilateral exchange rate index and the bilateral USD/CNY and USD/CNH exchange rates. This indicates that the USD/CNY and USD/CNH dynamics owed more to USD strength than renminbi weakness. Against the background of the CFETS development in November 2016, one could say that the pace of RMB depreciation against the USD was below average compared to those of other currencies against USD. In other words, the market expectations incorporated in the PDF operated on the assumption that the CNH would continue to depreciate against the USD and that China would seek to maintain competitiveness against its major trading partners through the US interest-rate normalization cycle.

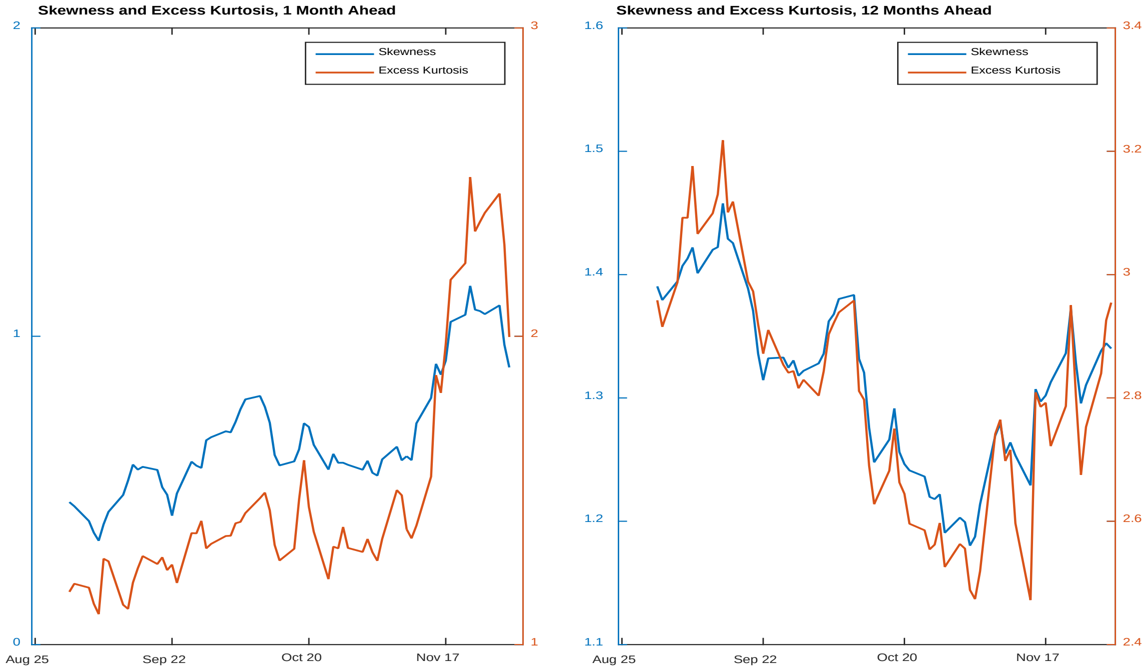
[21] The CFETS basket is heavily weighted in the majors of the USD, EUR and JPY, but is also adapted to the specific nature of China's trading landscape. The weights of currencies in CFETS RMB Index are 26.4% USD, 21.39% EUR, 14.68% JPY, 6.55% HKD, 6.27% AUD, 4.67% MYR, 4.36% RUB, 3.86% GBP, 3.82% SGD, 3.33% THB, 2.53% CAD, 1.51% CHF, and 0.65% NZD. The launch of the CFETS index does not necessarily imply the immediate adoption of a basket peg, but it may signify PBoC intent to move in that direction.

Figure 13 USD/CNH option-implied densities (4 November 2016– 14 November 2016)



Finally, the higher moments in Figure 14 show that market uncertainty increased substantially in November 2016 from previous levels. This was triggered by the increased risk aversion of global investors. The heightened risk awareness led markets to attach a greater likelihood to further gradual depreciation of the USD/CNH exchange rate. Said simply, the emphasis on the trade-weighted CFETS basket created significant pressure as investors anticipated that the RMB would depreciate further against the USD. Hence, despite the initial intention to move to a more market-orientated system, the final result appeared to be an opaque version of the old fixed rate system involving a morning fix based on the market rate of the previous day, itself determined by intervention in the onshore market.

Figure 14 Skewness and excess kurtosis coefficients, (1 September 2016 – 30 November 2016)



Our results overall confirm the usefulness of the RND approach in analyzing market sentiment and risk aversion in the RMB market. As demonstrated with these three case studies, the benefit of the approach is that one can zoom in on certain events and assess immediate market reactions. The changes in location and shapes of the daily RNDs illustrative the changes in assessment around the times of various episodes. Thus, monitoring CNH densities is useful to gauge information about sentiment and uncertainty in the RMB exchange rate. We now move beyond interpretive, ex-post storytelling. The real challenge is not to explain events after the fact, but to forecast exchange rates in real time.[22]

4 Forecast methodology and results

As a final step, we verify the out-of-sample forecasting properties of the estimated RNDs. As we focus on density forecasting,[23] our shape evaluation is based on entire estimated density.

[22] When testing for the forecasting properties of the RNDs, we address a potential proximate mechanism driving the exchange rate dynamics. Ultimate explanations are concerned with the deep root causes. In contrast, proximate explanations are concerned with the mechanisms that underpin the deep root causes.
[23] Corradi and Swanson (2006) provide an excellent review of various testing methods in density forecasting.

The first statistical tool is the well-known density test of Berkowitz (2001). It is based on the inverse normal transformed probability integral transformation (PIT), which is given by

$$y_t^\tau \equiv \Phi^{-1}(z_t^\tau) = \Phi^{-1}\left(\int_0^{S_{t+22\tau}} \pi_t^\tau(x)dx\right), \tag{11}$$

where z_t denotes the PIT and $\Phi^{-1}(x)$ the cumulative density function of an inverse normal distribution.[24] The main idea is that, under correct model specification, the PIT yields an independent and uniformly distributed random variable.

Based on the forecast horizon τ, the upper limit of the integral has to be chosen to be the realized spot exchange rate τ months in the future, $S_{t+22\tau}$. Berkowitz (2001) demonstrates that if the density forecast is accurate, the y_t time series should follow an independent and identical standard normal distribution.[25] To test this hypothesis jointly, the following regression is estimated:

$$y_t^\tau - \mu = \alpha(y_{t-1}^\tau - \mu) + \epsilon_t \, . \tag{12}$$

Given the log-likelihood $L(\hat{\mu}, \hat{\sigma}^2, \hat{\alpha})$ of (12), likelihood ratio tests for the null hypothesis of i.i.d. standard normality (LR_3) and for independence across observations (LR_1) are given by the following two test statistics, respectively:

$$LR_3 = -2[L(0,1,0) - L(\hat{\mu}, \hat{\sigma}^2, \hat{\alpha})] \sim \chi^2(3) \tag{13}$$

$$LR_1 = -2[L(\hat{\mu}, \hat{\sigma}^2, 0) - L(\hat{\mu}, \hat{\sigma}^2, \hat{\alpha})] \sim \chi^2(1) \tag{14}$$

Because the daily values of y_t are calculated from options with overlapping maturities, we must discard all realizations that lie in the forecasting range of a density. Thus, we can only use one observation per month with non-overlapping maturity for the one-month forward-looking RNDs. Hence, the sample size decreases significantly from $N = 1518$ to $N = 69$, making the Berkowitz (2001) test only feasible for the one-month maturity.

[24] In the original Berkowitz (2001) article, the lower integral bound is minus infinity. However, since a negative spot exchange rate cannot exist, the probability of such an outcome implied by the RND/RWD is zero. Thus, it is sufficient to calculate the integral with zero as a lower bound.
[25] See Clements (2004) for further details.

To overcome the disadvantage of shrinking sample size and wasting information, our second test procedure is the test proposed by Christoffersen and Mazzotta (2005), i.e. the CM test. Given the y_t series, the first four moments of its distribution can be estimated jointly by the following set of regressions using the Generalized Method of Moments (GMM):

$$\begin{aligned} y_t^{\tau} &= a_1 + \epsilon_{1,t} \\ (y_t^{\tau})^2 - 1 &= a_2 + \epsilon_{2,t} \\ (y_t^{\tau})^3 &= a_3 + \epsilon_{3,t} \\ (y_t^{\tau})^4 - 3 &= a_4 + \epsilon_{4,t} \end{aligned} \tag{15}$$

Under the null of standard normally distributed y_t's, all coefficients a_i $(i = 1, \dots, 4)$ should be zero. Every coefficient a_i is tested for significance individually. Moreover, the coefficients can be tested jointly by applying a Wald test. To deal with the overlapping nature of the PITs, Newey-West standard errors are used. Therefore, no density has to be discarded making it possible to test the forecasting ability of the RNDs for all maturities.[26]

Whether or not the CNH is a good proxy for the CNY is a difficult question. On one hand, market participants maintain that the offshore CNH market provides genuine price discovery, free from the influence of onshore interventions at least partially driven by political considerations. There are plenty of precedents where offshore FX market prices more closely resemble reality than official policy views at the time. On the other hand, it may be that high-frequency CNH traders exacerbate volatility in less certain times. For this reason, the impact the offshore CNH market has on onshore CNY prices appears to be an unanswered question. To analyze the information content of the CNH FX option market for the CNY, we use CNH RNDs to test their forecasting ability for the CNY by applying the inverse normal PIT transformation of (11) for the CNY/USD realizations.

The Berkowitz forecast results for the CNH and the CNY exchange rates and one-month maturity are presented in Table 1. The null hypothesis of i. i. d. standard normal y_t^{1m}'s is rejected in both cases as can be seen by the LR_3 statistic. Although we have a sample with non-overlapping maturities, the LR_1 statistic rejects the null hypothesis of independently distributed y_t^{1m}'s both for the CNH and the CNY. In other words, the RNDs do not properly forecast the true densities.

[26] Since we are dealing with five days of daily data, we apply a Newey-West correction with a Bartlett window of six lags to account for the autocorrelation one week backwards. Applying lags up to 12 produces similar results, indicating robustness.

Table 1 Berkowitz (2001) density tests

	$\underline{CNH}$		$\underline{CNY}$	
	$Test\text{-}Value$	$P\text{-}Value$	$Test\text{-}Value$	$P\text{-}Value$
LR_3 $Statistic$	8.5852	0.0353	9.5599	0.0227
LR_1 $Statistic$	5.1070	0.0238	7.7669	0.0053

Notes: The table shows results of the Berkowitz test. The null hypothesis of the LR_3 is H_0: $y_t^1 \sim iid\ N(0,1)$, and for the LR_1 it is H_0: $y_t^1 \sim$ independent distribution. LR_3 and LR_1 follow χ^2-distribution with 3 and 1 degrees of freedom. The inverse normal transformed PITs are chosen to be non-overlapping, leading to a sample size of $N = 69$.

Now we turn to the CM test. The CM test can deal with the autocorrelation in the y_t^τ's by applying robust standard errors, making it possible to conduct forecast evaluation for *all* maturities. In addition, the CM test provides clues as to why the standard normal hypothesis for the y_t^τ's is rejected. Table 2 shows results for the CM test for CNH and CNY density forecasts at maturities of one to twelve months. Bold typed values show a non-rejection of the null hypothesis at the 5 percent level. The joint Wald test indicates that the y_t^τ's are not normally distributed for all maturities.

A closer look at the first four estimated moments offers interesting insights. For $\tau = 1M$ the null of standard normality is rejected due to a misspecification of the mean, indicating that the RNDs specify all other moments correctly for the CNH and CNY exchange rate distributions at maturity. For $\tau = 6M$ there is evidence that the tails are specified correctly and for $\tau = 12M$ the mean estimates do not contradict the null hypothesis of being equal to zero for both CNH and CNY.

Table 2 Christoffersen and Mazzotta (2005) density tests

	CNH		*CNY*	
	Coef	*P-Value*	*Coef*	*P-Value*
		1-M		*1-M*
Mean (a_1)	–0.168	0.017	–0.187	0.003
Variance (a_2)	0.207	0.094	0.008	0.940
Skewness (a_3)	0.056	0.894	–0.360	0.272
Excess Kurtosis (a_4)	2.496	0.065	0.962	0.333
Wald-test	16.04	0.003	18.88	0.001
		3-M		*3-M*
Mean (a_1)	–0.274	0.001	–0.302	0.000
Variance (a_2)	0.467	0.000	0.409	0.001
Skewness (a_3)	–1.204	0.004	–1.194	0.002
Excess Kurtosis (a_4)	2.844	0.014	2.368	0.027
Wald-test	23.87	0.000	23.88	0.000
		6-M		*6-M*
Mean (a_1)	–0.223	0.003	–0.236	0.001
Variance (a_2)	0.211	0.013	0.148	0.060
Skewness (a_3)	–0.989	0.000	–0.930	0.000
Excess Kurtosis (a_4)	–0.062	0.861	–0.411	0.180
Wald-test	377.45	0.000	629.08	0.000
		12-M		*12-M*
Mean (a_1)	–0.141	0.158	–0.153	0.113
Variance (a_2)	0.823	0.000	0.711	0.000
Skewness (a_3)	–1.877	0.000	–1.765	0.000
Excess Kurtosis (a_4)	4.862	0.000	4.026	0.002
Wald-test	70.95	0.000	71.35	0.000

Notes: The table shows results for the CM test. All coefficients are tested individually by t-tests with $\mathrm{H_0}: \mathrm{a_i} = 0$ for $\mathrm{i} = 1, \ldots, 4$ and jointly by the Wald-test with $\mathrm{H_0}: \mathrm{a_1} = \cdots = \mathrm{a_4} = 0$. To correct the standard errors for heteroscedasticity and autocorrelation (HAC) in the overlapping PITs, Newey-West HAC estimators for the covariance matrices are used. The chosen lag length is chosen is 6 for all maturities. The sample sizes are $N_{1m} = 1518$, $N_{3m} = 1474$, $N_{6m} = 1408$ and $N_{12m} = 1276$, respectively.

Finally, to investigate whether the mapping between the RNDs and the future CNH and CNY exchange rates become tighter or looser over time, we split the sample and calculate the density tests before and after the exchange rate regime change on 11 August 2015, the date when the authorities took an important step in making the RMB more market determined by making the morning fixing rate (against which intervention bands are calculated) dependent on market prices from the previous day. At the time, the move was seen as a signal that the authorities were interested in moving to a more market-based exchange rate system. The results for maturities of one, three, six and twelve months are presented in Table 3. For $\tau = 1M$ the RND forecast for the CNY in the first half is misspecified in the mean, while for the CNH only the third moment is correctly described. In the second sub-sample, only the variance is correctly specified for the CNH, while for the CNY the mean is correctly specified.

Table 3 Christoffersen and Mazzotta (2005) sample split density tests

	05/09/2011 to 11/08/2015				12/08/2015 onward			
	CNH		CNY		CNH		CNY	
	$Coef$	P-$Value$	$Coef$	P-$Value$	$Coef$	P-$Value$	$Coef$	P-$Value$
	1-M		1-M		1-M		1-M	
$Mean\ (a_1)$	–0.300	0.001	–0.297	0.000	0.194	0.046	0.112	**0.205**
$Var\ (a_2)$	0.409	0.012	0.188	**0.182**	–0.348	0.000	–0.484	0.000
$Skew\ (a_3)$	0.017	**0.976**	–0.499	**0.261**	0.162	**0.264**	0.022	**0.839**
$Kurt\ (a_4)$	4.184	0.022	2.199	**0.101**	–2.126	0.000	–2.427	0.000
$Wald$-$test$	34.81	0.000	26.06	0.000	660.7	0.000	2507.7	0.000
	3-M		3-M		3-M		3-M	
$Mean\ (a_1)$	–0.487	0.000	–0.510	0.000	0.358	0.000	0.321	0.000
$Var\ (a_2)$	0.742	0.000	0.671	0.000	–0.439	0.000	–0.460	0.000
$Skew\ (a_3)$	–1.692	0.002	–1.653	0.001	0.347	0.000	0.274	0.001
$Kurt\ (a_4)$	4.467	0.003	3.860	0.005	–2.473	0.000	–2.526	0.000
$Wald$-$test$	50.09	0.000	51.48	0.000	13305	0.000	13101	0.000
	6-M		6-M		6-M		6-M	
$Mean\ (a_1)$	–0.411	0.000	–0.426	0.000	0.547	0.000	0.545	0.000
$Var\ (a_2)$	0.412	0.000	0.334	0.000	–0.603	0.000	–0.599	0.000
$Skew\ (a_3)$	–1.310	0.000	–1.235	0.000	0.312	0.000	0.911	0.000
$Kurt\ (a_4)$	0.596	**0.158**	0.162	**0.659**	–2.738	0.000	–2.742	0.000
$Wald$-$test$	242.9	0.000	414.9	0.000	78301	0.000	64077	0.000
	12-M		12-M		12-M		12-M	
$Mean\ (a_1)$	–0.271	0.012	–0.286	0.006	0.893	0.000	0.902	0.000
$Var\ (a_2)$	0.947	0.000	0.821	0.000	–0.137	**0.105**	–0.137	**0.072**
$Skew\ (a_3)$	–2.228	0.000	–2.098	0.000	0.878	0.000	0.863	0.000
$Kurt\ (a_4)$	5.753	0.000	4.812	0.001	–2.074	0.000	–2.108	0.000
$Wald$-$test$	50.22	0.000	48.32	0.000	16574	0.000	46659	0.000

Notes: The table shows results for the C&M test. All coefficients are tested individually by t-tests with $H_0: a_i = 0$ for $i = 1, \ldots, 4$ and jointly by the Wald-test with $H_0: a_1 = \cdots = a_4 = 0$. To correct the standard errors for heteroscedasticity and autocorrelation in the overlapping PITs, Newey-West HAC estimators for the covariance matrices are used. The lag length is chosen to be 6 for all maturities. The sample sizes for the first half for all maturities is $N = 1112$. The sample sizes for the second half are $N_{1m} = 406$, $N_{3m} = 362$, $N_{6m} = 296$, and $N_{12m} = 164$.

In line with these findings, the Wald tests for τ =1M indicate that the RNDs have no forecasting power in the second sub-sample. For maturities over a month, Table 3 shows consistent evidence against the RNDs. In other words, for longer horizons, the forecasts are hardly impressive and density forecasts remain an open challenge. Put differently, the results underpin the notion that the CNH and CNY are imperfect substitutes and priced differently to some degree.

Summarizing the above, the two out-of-sample forecasting tests yield mixed results. We find evidence for some forecasting ability between July 2011 and March 2017. The one-month forward looking RNDs characterize the variance, skewness, and excess kurtosis of the actual density at maturity correctly, while the mean is misspecified. Therefore, market participants are able to forecast the shape of the actual densities correctly for short horizons, while its exact location cannot be determined. These findings have relevance for policymakers and financial market participants interested in future developments of the CNH and CNY.[27]

5 Conclusions

As part of the RMB internationalization process, China created an offshore RMB market to maintain the capital controls and regulations. Among offshore RMB clearing hubs, Hong Kong has become the central hub for RMB settlement with a wide range of RMB products and services available. Using the information of exchange US dollar/offshore renminbi exchange rate option prices, we applied “volatility smile” interpolation method and the method of Malz (1996, 1997a, 1997b, 2014) to derive parametric risk-neutral densities (RNDs), as well as recover risk-neutral probability densities for the implied future US dollar/offshore renminbi exchange rates.

This paper confirms the usefulness of the RND approach in analyzing market sentiment and risk aversion in the RMB market. The changes in location and shapes of daily RNDs are illustrative of the changes in assessment by market participants around the times of various episodes. Thus, monitoring CNH densities provides a useful gauge of sentiment and uncertainty in the RMB exchange rate.

Despite the propensity of China’s authorities to intervene in the CNH market when market volatility is high (Cheung et al., 2017), we support the general view that there is an informational role for the offshore CNH market in reflecting market expectations and sentiment.

In all of the case studies presented here, the proposed method makes it possible to zoom in on market events and immediate market reactions. The CNH market provides information about supply and demand with minimal distortion induced from the official intervention in normal time. For instance, before the reform of fixing mechanism of RMB onshore rate in August 2015, the

[27] The failure of the densities to accurately explain future FX rates should not be surprising. The forecasting contribution of standard exchange rate models has been under question since the seminal paper of Messe and Rogoff (1983). See Rossi (2013) for a review of the recent exchange rate forecasting literature.

1- month-ahead skewness and excess kurtosis indicate that the depreciation was not entirely unexpected. Already at the beginning of July 2015, both higher moments increased significantly, reflecting a change in the market assessment.

To investigate the predictive power of the estimated probability density of CNH futures, we applied two out-of-sample forecasting tests and found evidence for some forecasting ability between July 2011 and March 2017. The 1-month forward-looking RNDs correctly characterize the variance, skewness, and excess kurtosis of the actual density at maturity, but the mean is misspecified. The implication is that market participants are able to forecast the shape of the actual densities correctly for short horizons, while their exact location cannot be determined accurately. These findings about the informational content of CNH market could have relevance for policymakers and financial market participants interested in future developments of the CNH and CNY.

Along with other methods, RMB watchers can well benefit from options-based probability density functions at various maturities. The need for further research, including the relationship between market expectations and policy responses to market sentiment, seems quite apparent.

References

Anderson, E.W., E. Ghysels and J.L. Juergens (2009). "The Impact of Risk and Uncertainty on Expected Returns," Journal of Financial Economics 94, 233–263.

Bahra, B. (1996). "Probability Distributions of Future Asset Prices Implied by Option Prices," Bank of England Quarterly Bulletin 39, 384–392.

Bahra, B. (1997). "Implied Risk-Neutral Probability Density Functions from Option Prices: Theory and Application," Bank of England Working Paper 66, London.

Bank of England (2015). "Deriving Option-Implied Probability Densities for Foreign Exchange Markets," Center for Central Bank Studies, Technical Handbook 5, London.

Berkowitz, J. (2001). "Testing Density Forecasts, with Applications to Risk Management," American Statistical Association 19, 465–474.

BIS (2016). Quarterly Review, March 2016, Basel.

Bliss, R.R. and N. Panigirtzoglou (2002). "Testing the Stability of Implied Probability Density Functions," Journal of Banking and Finance 26, 381–422.

Bliss, R. and N. Panigirtzoglou (2004). "Option-Implied Risk Aversion Estimates," Journal of Finance 59, 407–446.

Breeden, D.T. and R.H. Litzenberger (1978). "Prices of State-Contingent Claims Implicit in Option Prices," Journal of Business 51, 621–651.

Campa, J., K. Chang and R. Reider (1998). "Implied Exchange Rate Distributions: Evidence from OTC Option Markets," Journal of International Money and Finance 17, 117–160.

Cheung, Y.-W., C.-H. Hui and A. Tsang (2016). "The Renminbi Central Parity: An Empirical Investigation," HKIMR Working Paper No. 10/2016, Hong Kong.

Christoffersen, P. and S. Mazzotta (2005). "The Accuracy of Density Forecasts from Foreign Exchange Options," Journal of Financial Econometrics 3, 578–605.

Clements, M.P. (2004). "Evaluating the Bank of England Density Forecasts of Inflation," Economic Journal 114, 844–866.

Cochrane, J.H. (2017). "Macro-Finance," Review of Finance 21, 945–985.

Corradi, V. and N. Swanson (2006). "Predictive Density Evaluation," in: Elliott, G., C.W.J. Granger and A. Timmermann (eds.), Handbook of Economic Forecasting, Vol. 1, 197–284, Amsterdam (Elsevier).

Della Corte, P., T. Ramadorai and L. Sarno (2016). "Volatility Risk Premia and Exchange Rate Predictability," Journal of Financial Economics 120, 21–40.

De Santis, G. and B. Gèrard (1998). "How Big is the Premium for Currency Risk?" Journal of Financial Economics 49, 375–412.

Eichengreen, B. and M. Kawai (2015). Renminbi Internationalization – Achievements, Prospects and Challenges. Washington and Tokyo.

Farhi, E. and X. Gabaix (2016). "Rare Disasters and Exchange Rates," Quarterly Journal of Economics 131, 1–52.

Funke, M., Shu, C., Cheng, X. and S. Eraslan (2015). "Assessing the CNH-CNY Pricing Differential: Role of Fundamentals, Contagion and Policy," Journal of International Money and Finance 59, 245–262.

Giordani, P. and P. Söderlind (2003). "Inflation Forecast Uncertainty," European Economics Review 47, 1037–1059.

Gürkaynak, R. and J. Wolfers (2005). "Macroeconomic Derivatives: An Initial Analysis of Market-Based Macro Forecasts, Uncertainty, and Risk." In Frankel, J.A. and C.M. Pissarides (eds.), NBER International Seminar on Macroeconomics 2005, 11–50.

Harrison, J.M. and D.M. Kreps (1979). "Martingales and Arbitrage in Multiperiod Securities Markets," Journal of Economic Theory 20, 381–408.

Jackwerth, C.J. (2000). "Recovering Risk Aversion from Option Prices and Realized Returns," Review of Financial Studies 13, 433–451.

Jondeau, E. and M. Rockinger (2000). "Reading the Smile: The Message Conveyed by Methods Which Infer Risk Neutral Densities," Journal of International Money and Finance 19, 885–915.

Kandel, S. and R.F. Stambaugh (1991). "Asset Returns and Intertemporal Preference," Journal of Monetary Economics 27, 39–71.

Liu, X., M.B. Shackelton, S.J. Taylor and X. Xu (2007). "Closed-Form Transformations from Risk-Neutral to Real-World Distributions," Journal of Banking and Finance 31, 1501–1520.

Lynch, D. and N. Panigirtzoglou (2004). "Using Option Prices to Measure Financial Market Views about Balances of Risk to Future Asset Prices," Bank of England Quarterly Bulletin 44 (4), 442–454.

Malz, A.M. (1996). "Using Option Prices to Estimate Realignment Probabilities in the European Monetary System: The Case of Sterling-Mark," Journal of International Money and Finance 15, 717–748.

Malz, A.M. (1997a). "Estimating the Probability Distribution of the Future Exchange Rate from Option Prices," Journal of Derivatives 5, 18–36.

Malz, A.M. (1997b). "Option-Implied Probability Distributions and Currency Excess Returns," Staff Reports, Federal Reserve Bank of New York, No. 32, New York.

Malz, A.M. (2014). "A Simple and Reliable Way to Compute Option-Based Risk-Neutral Distributions," Staff Reports, Federal Reserve Bank of New York No. 677, New York.

Meese, R.A., and K. Rogoff (1983). "Empirical Exchange Rate Models of the Seventies: Do They Fit Out of Sample?" Journal of International Economics 14, 3–24.

Mehra, R. and E.C. Prescott (1985). "The Equity Premium: A Puzzle," Journal of Monetary Economics 15, 145–161.

Mirkov, N., I. Pozdeev and P. Söderlind (2016). "Toward Removal of the Swiss Franc Cap: Market Expectations and Verbal Interventions," SNB Working Paper No. 2016–09, Zürich.

Romer, D. (2012). Advanced Macroeconomics, 4th edition. New York (McGraw-Hill).

Rossi, B. (2013). "Exchange Rate Predictability," Journal of Economic Literature 51, 1063–1119.

Shimko, D.C. (1993). "Bounds of Probability," RISK 6, 33–37.

Appendix Recovering real-world USD/CNH densities

Real-world densities (RWDs) can be recovered from risk-neutral densities (RNDs) by making assumptions about risk preferences.[28] Jackwerth (2000) provides an elegant transformation of RNDs into RWDs, showing that the risk neutral probability is equal to the real-world probability times a risk-aversion adjustment. In other words, the RWD is basically a by-product of the benchmark RND and the degree of risk aversion. Bearing this in mind, RWDs can be derived by considering specific utility functions to describe risk preferences. Bliss and Panigirtzoglou (2004) employ the CRRA utility function

$$u(x) = \frac{x^{1-\rho} - 1}{1 - \rho}, \tag{A1}$$

where ρ is the relative risk aversion parameter.[29] In the case of the CRRA utility function, the relation between the RND, given by $\pi_t^\tau(x)$, and the RWD, denoted by $q_t^\tau(x)$, is given by

$$q_t^\tau(x) = \frac{\frac{\pi_t^\tau(x)}{u'(x)}}{\int_0^\infty \frac{\pi_t^\tau(y)}{u'(y)} dy} = \frac{x^\rho \pi_t^\tau(x)}{\int_0^\infty y^\rho \pi_t^\tau(y) dy}, \tag{A2}$$

where x and y stand for the potential realizations of the exchange rate at expiration. The term in the numerator of (A2) adjusts RND to account for the risk preferences of the representative agent, while the term in the denominator rescales the transformed function such that it integrates to unity and hence represents probabilities. Liu et al. (2007) also use this elegant transformation.

We now proceed to back out the RWDs for a range of values for the risk-aversion parameter found in the literature. A plausible assumption here is that the relative risk-aversion parameter is in the range of $3 < \rho < 10$. Indeed, several authors argue that ρ = 3 can well serve as a first-order approximation for real-world risk-taking behavior in financial markets. Bliss and Panigirtzoglou (2004) and Liu et al. (2007) find relative risk-aversion parameters between 2 and 4. Mehra and Prescott (1985) impose an upper bound of 10 for the relative risk-aversion parameter.[30]

[28] The distinction between RNDs and RWDs is formalized in Harrison and Kreps (1979).
[29] We do not assume here that all agents have CRRA utility. Instead, we implicitly take the view that it is reasonable to take the perspective of such an agent as a benchmark.
[30] A few authors in the financial literature argue that a risk-aversion coefficient in the range of $20 < \rho < 30$ is needed to account for the equity premium puzzle. See, for example, Kandel and Stambaugh (1991). Such a high level of risk

Figure A1 presents 1-month-ahead RNDs and RWDs for four dates between 9 May 2011 and 31 March 2017. Each of these dates is considered representative of its time period. It is apparent that the 1-month-ahead densities are almost the same for reasonable risk-aversion parameters.[31]

Figure A2 presents the 6-months-ahead densities for the same dates. As is apparent from the figure, the right tail for the recovered RWDs is more leptokurtic than the corresponding RNDs.

Figure A3 and A4 present plots of the first, third, and fourth moments of the RWDs for $\rho = 3$ and $\rho = 10$ over the entire sample period. Again, the means of both measures are nearly identical, while the higher moments of the RNDs are fatter tailed than the RWDs for exceptionally high $\rho's$.

aversion is implausible. The relative risk aversion parameter $\rho = 25$, for example, implies that agents would accept a 17% reduction in consumption with certainty rather than a 50:50 chance of a 20% reduction (Romer, 2012, p. 388).

[31] This finding is expected. Gürkaynak and Wolfers (2007) show that the risk-neutrality assumption cannot be rejected in a market for institutional investors. Mirkov et al. (2016) estimate RNDs and RWDs for the future CHF/EUR exchange rate from option implied densities by adjusting the mean of the RND by the currency-risk premium. Both are found to be quite similar. Moreover, De Santis and Gèrard (1997) find that the risk premium is small on average in foreign exchange markets, further indicating that our calculations are plausible.

Figure A1 Option-implied RNDs and RWDs, 1 month ahead

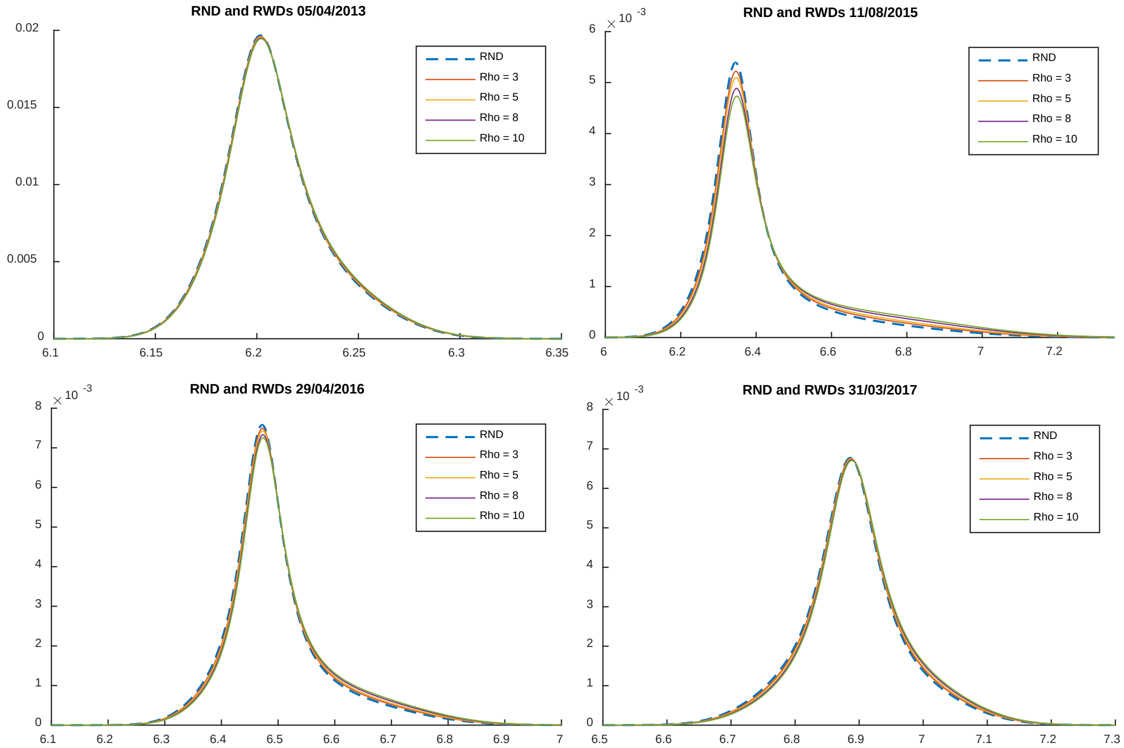


Figure A2 Option-implied RNDs and RWDs, 6 months ahead

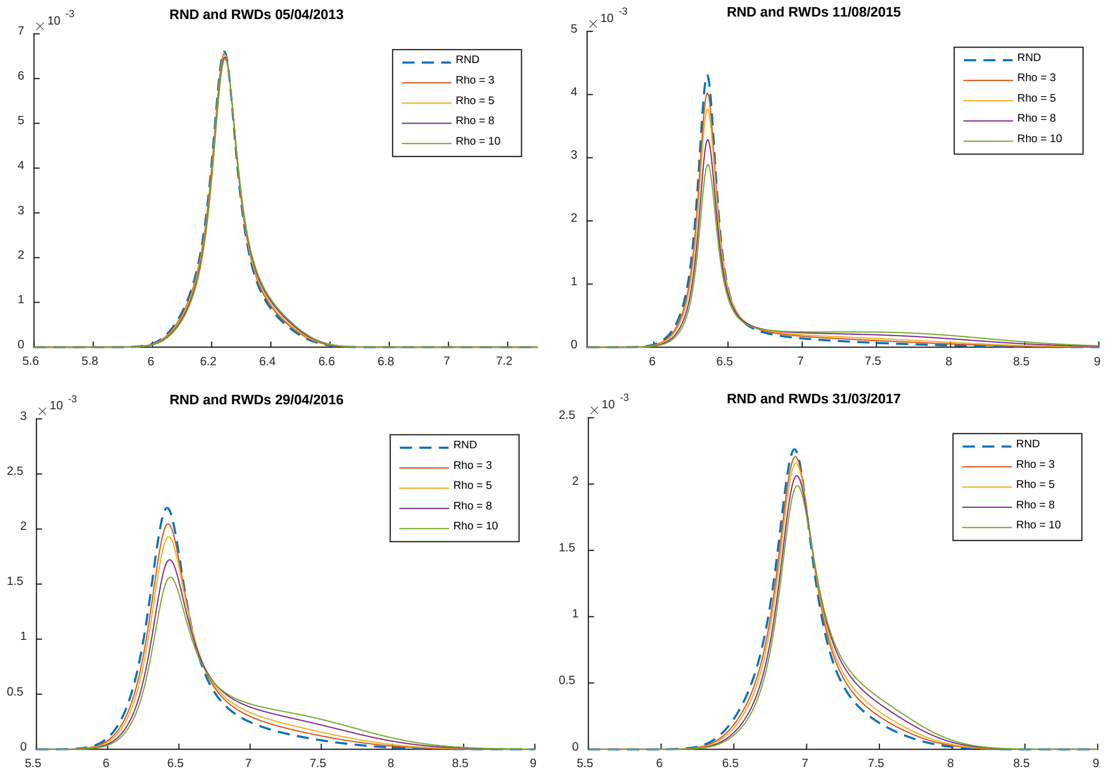


Figure A3 Time series of option-implied RND and RWD moments, $\rho = 3$

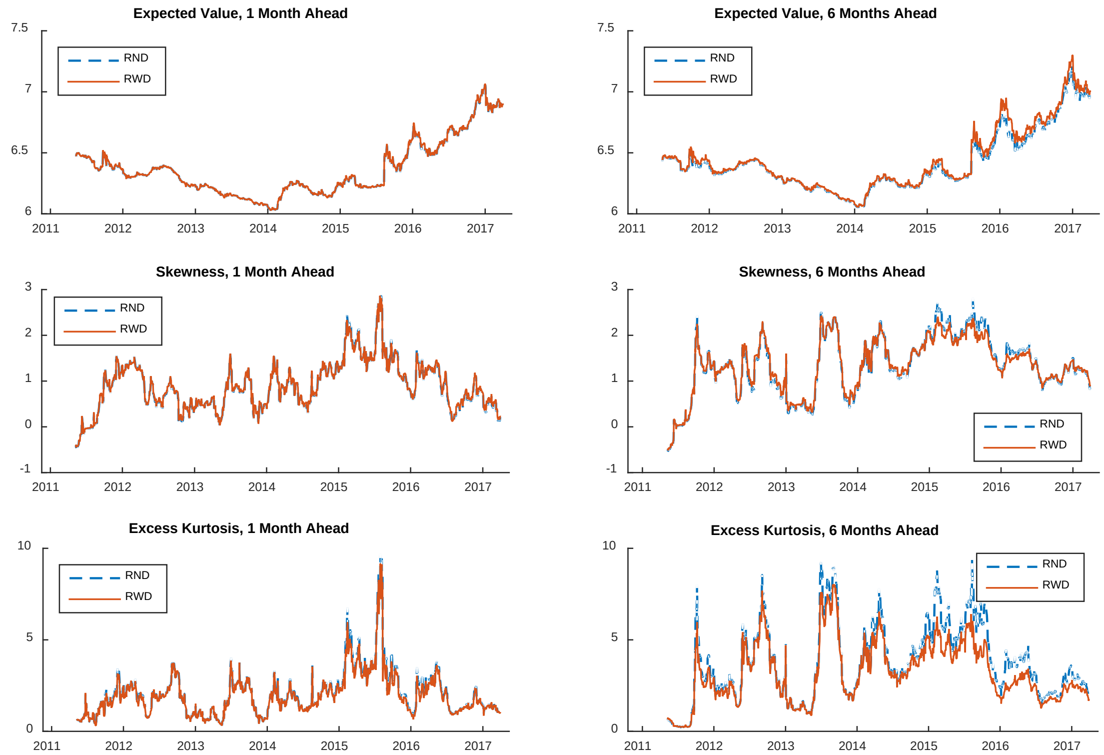
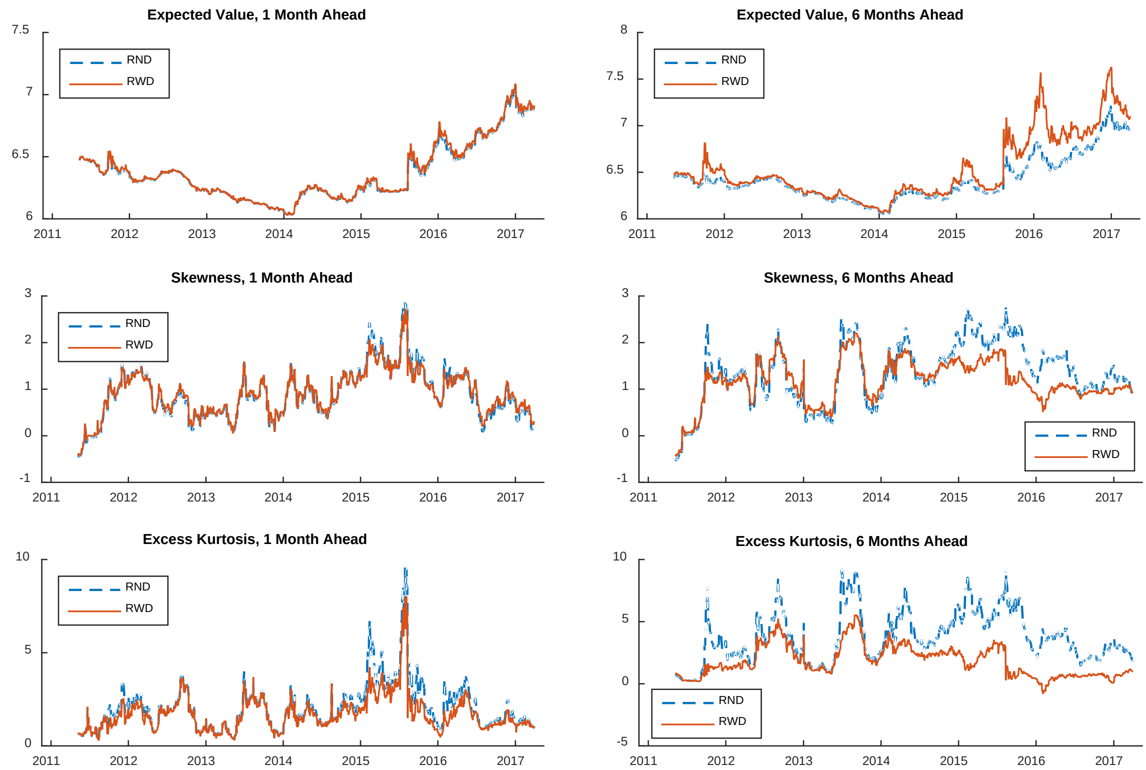


Figure A4 Time series of option-implied RND and RWD moments, $\rho = 10$



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