Foreign Exchange Options and the Economics of Exchange Rates

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Abstract

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Chapter One

Historically, the currency derivative pricing literature and the macroeconomics literature on FX determination have progressed separately. In this Chapter I argue the joint study of these two strands of literature and give an overview of FX option pricing concepts and terminology crucial for this interdisciplinary study. I also explain the three sources of information about market expectations and perception of risk that can be extracted from FX option prices and review empirical methods for extracting option-implied densities of future exchange rates. As an illustration, I conclude the Chapter by investigating time series dynamics of option-implied measures of FX risk vis-a-vis market events and US government policy actions during the period January 2007 to December 2008.

Chapter Two

This Chapter proposes using foreign exchange (FX) options with different strike prices and maturities to capture both FX expectations and risks. We show that exchange rate movements, which are notoriously difficult to model empirically, are well-explained by the term structures of forward premia and options-based measures of FX expectations and risk. Although this finding is to be expected, expectations and risk have been largely ignored in empirical exchange rate modeling. Using daily options data for six major currency pairs, we first show that the cross section options-implied standard deviation, skewness and kurtosis consistently explain not only the conditional mean but also the entire conditional

distribution of subsequent currency excess returns for horizons ranging from one week to twelve months. This robust empirical pattern is consistent with a representative expected utility maximizing investor who, in addition to caring about the mean and variance, also cares about the skewness and kurtosis of the return distribution. Our results highlight the importance of expectations and risk in explaining exchange rate dynamics and suggest that the perennial problems faced by the empirical exchange rate literature are most likely due to overly restrictive auxiliary assumptions inherent in prevailing testing methods.

Chapter 3

Standard ordinary least squares (OLS)-based tests of the uncovered interest parity (UIP) condition often make strong auxiliary assumptions beyond the joint hypotheses of rational expectations and risk-neutrality. This paper proposes using prices of foreign exchange (FX) option with different strike prices to test the time-varying risk premia explanation of the UIP puzzle. The options-based testing framework rests on the theoretical result that the forward exchange rate is the theoretical first moment of the option-implied distribution of future spot exchange rate. The framework allows us to test a more general version of FX market efficiency, which is the hypothesis that the option-implied risk-neutral distribution is an unbiased predictor of the future realized distribution of future spot rate. For five currency pairs, I do not reject the null hypothesis of UIP using the options-based approach.

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Chapter 1

FX OPTIONS AND THE ECONOMICS OF EXCHANGE RATES: AN OVERVIEW

1.1 Introduction

The economics of exchange rates is one of the most important sub-fields of economics. This is because understanding the determinants of exchange rates and the ability to accurately forecast future exchange rate dynamics is important for issues such as:

- facilitating investment and hedging decisions for investment or financial risk managers who hold international portfolios,
- evaluating the domestic values of a country's foreign reserves, foreign denominated debt payments and remittances from citizens working abroad, and
- evaluating import and export prices.

The above issues have implications for a country's macroeconomic variables such as wages, output and employment, and ultimately affect the welfare of a country's population.

The economics of exchange rates is also a sub-field of economics that is filled with a myriad of empirical irregularities or "puzzles". For example, over the last three decades, researchers have found it very difficult to find an empirical link between exchange rates and macroeconomics variables. This is despite economic theory suggesting that nominal exchange rates should be determined by macroeconomic variables such as output and inflation.[1] Furthermore, starting with the seminal work of Meese and Rogoff (1983), it is well documented that such macro-based exchange rate models perform poorly in out-of-sample

[1] "There seems to be very little evidence that the supposed determinants of exchange rates -monetary policy and determinants of real income and inflation-can explain exchange rate movements." Engel (2013)

forecasting.[2]

Another exchange rate anomaly is the empirical failure of the uncovered interest parity (UIP) condition, which predicts that exchange rates of high interest currencies should subsequently depreciate, so that the simple carry trade investment strategy of borrowing from low interest rate currencies and investing in high interest currency should have an average return of zero over time. One implication of the UIP condition is that the forward exchange rate is an unbiased predictor of future spot rates. Empirically, however, high interest rate currencies tend to appreciate and such carry trade strategies tend to yield positive returns on average, resulting in the "UIP puzzle"' or "forward premium puzzle."

In this Chapter, I argue for the use FX option price data and empirical techniques to address questions in the economics of exchange rates. On one hand, we have empirical exchange rate puzzles such as those just mentioned, and some of these puzzles can be attributed to the failure of standard empirical methods to capture market participants' expectations and perceptions of risk. On the other hand, the literature on exchange rate economics and that on foreign exchange (FX) derivative pricing have traditionally evolved separately, in spite of FX option prices theoretically containing market-based and forward-looking measures of risk and expectations beyond that contained in interest rates or forward contracts. Chen (1998) notes that graduate international economics classes do not typically cover FX derivatives, while standard graduate finance courses tend to focus on the pricing techniques for currency derivatives with little emphasis on the economics of exchange rate determination. Furthermore the recent growth in the FX options market, has facilitated more reliable empirical analysis using FX options. Last, there has been significant developments in the methodologies for extracting this option-implied information. Bridging the gap between exchange rate economics is not only important for academic researchers, but can be also be useful for practitioners such as central bank economists and financial investment and risk managers who hold internationally diversified portfolios.

The rest of this chapter proceeds as follows: In section (1.2) I introduce the basics of option pricing theory as well as some FX option market quoting conventions. In section

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[2] "From the early 1980s, exchange rate forecasting in general became a hazardous occupation, and this remains largely the case" Clarida et al. (2003)

(1.3) I explain the theoretical information content of option price data as well as give a brief overview of the empirical methods for extracting this information. Finally, to illustrate an example of how option-implied information can be used to link exchange rate dynamics to macroeconomic events, in section (1.4) I relate the time series dynamics of option-implied moments to macroeconomic and financial market events during the financial crisis of 2008. Section (1.5) concludes the Chapter.

1.2 FX Option pricing mechanics and market conventions

A derivative is a financial instrument whose value depends[3] on the value of another underlying variable such as stock price, exchange rate or the weather. A call option gives the holder the right to buy the underlying asset by a certain date (the maturity date) for a certain pre-agreed price K (the "exercise" or "strike" price). The seller of a call option is obligated to sell the underlying asset at the agreed exercise price at or before maturity. A put option gives the holder the right but not the obligation to sell the underlying asset by at the strike price K at or before the maturity date, while the seller of the put option option is obligated to sell at the pre-agreed exercise price.

To highlight the rich information content of option prices, I is useful to contrast options with another type of derivative contract, a forward contract. The holder of a forward contract, is obligated to buy the underlying asset at the agreed exercise price. Profit and loss diagrams for forward and option contracts are shown in figure (1.1). As can be seen from figure (1.1), the payoff to forward contract is linear in the spot price, while the payoffs to options are non-linear. This non-linear pay-off structure of options is what makes them more informative about market's expectations and perceptions of risk.

The moneyness of an option refers to whether it would be profitable to exercise the option. A call option is in-the-money if the spot exchange rate is greater than than the strike price, such than the holder of the option has an incentive to exercise the option. A call option is at-the-money if the exercise price is equal to the spot price, and out-of-the-money if the spot price is less than the the exercise price. Similarly, a put option is in-the-money if

[3] i.e. is derived from

the exercise price is greater than the spot price, and out-of-the-money if the exercise price is less than the spot price.

A foreign exchange derivative is a derivative in which the underlying asset is the spot exchange rate. European-style options can only be exercised at maturity, while American-style options can be exercised at or before maturity. Options can either be traded over-the-counter (o-t-c) or on an exchange. O-t-c markets are decentralized markets where the market participants trade with each other through mediums such as telephones. A derivative exchange is a highly centralized market where individuals trade standardized contracts defined by the exchange.

1.2.1 Option Pricing Model and Formula

To be able to understand the information about expectations and risk, it is necessary to have a basic understanding of option pricing techniques. The seminal work for option pricing is Black and Scholes (1973), who considered the problem of valuing a European-style stock option. The Black and Scholes (1973) model rests on a number of assumptions:

- The underlying price follows a log-normal distribution,
- The risk-free interest rate is known and does not change over time,
- It is possible to borrow any fraction of the price of a security to buy it,
- The underlying stock pays no dividends, and
- No transaction costs in buying and selling the underlying stock or the option.

With the above assumptions, Black and Scholes (1973) obtained the following expression for the price for a European-style option with tenor τ:

$$C(\tau, K, S, r, \sigma) = S_t \Phi(d_2) - e^{-r} K \Phi(d_1) \tag{1.2.1a}$$

$$d_1 = \frac{(ln[\frac{S}{K}] + (r - \frac{\sigma^2}{2}))}{\sigma\sqrt{\tau}} \tag{1.2.1b}$$

$$d_2 = \frac{(ln[\frac{S}{K}] + (r - \frac{\sigma^2}{2}))}{(\sigma\sqrt{\tau})} = d_1 + \sigma\sqrt{\tau}. \tag{1.2.1c}$$

In equation (1.2.1), Φ is the standard normal cumulative density function, σ is the annualized volatility and r is the risk-free interest rate. Garman and Kohlhagen (1983) extend the Black and Scholes (1973) model to the case of European-style foreign exchange options, and showed that the price of an FX call option with strike price K is given by :

$$C(\tau, K, S, r^d, r^f, \sigma) = e^{-r^f} S_t \Phi(d_2) - e^{-r^d} K\Phi(d_1) \tag{1.2.2a}$$

$$d_1 = \frac{(ln[\frac{S}{K}] + (r^d - r^f - \frac{\sigma^2}{2}))}{\sigma\sqrt{\tau}} \tag{1.2.2b}$$

$$d_2 = \frac{(ln[\frac{S}{K}] + (r^d - r^f + \frac{\sigma^2}{2}))}{(\sigma\sqrt{\tau})} = d_1 + \sigma\sqrt{\tau} \tag{1.2.2c}$$

where r^d and r^f are the domestic and foreign risk-free interest rates. The price of a European-style put option can be shown to equal:

$$P(\tau, K, S, r^d, r^f, \sigma) = -S_t\Phi(-d_2) + e^{r^d\tau} K\Phi(-d_1). \tag{1.2.3}$$

For a given tenor, the relationship between C, the price of a call option and P, the price of a put is called the put-call parity and is represented as follows:

$$P = C - S + Ke^{-r\tau}. \tag{1.2.4}$$

1.2.2 FX Options Market Growth and Quoting Conventions

Over the last 20 years, the world FX options market has experience significant growth. Table (1.1C) shows that the FX options market grew by 98.3% between 2001 and 2004, and by 83% between 2004 and 2007 when measured in terms of daily turnover. Overall, the o-t-c FX options market grew by 287% between 1998 and 2013. This increased liquidity makes o-t-c FX option prices more attractive for conducting empirical analysis, when compared to exchange-traded FX options. This is because prices obtained from a more liquid market are more reliable for the purpose of learning about market's expectations and perceptions of risk than prices from a thinly traded market.

While liquidity is a big consideration in choosing between o-t-c FX options and exchange traded options, there are other advantages that come with using o-t-c options compared to exchange-traded options. First, exchange traded options mature at a particular date. This means that the time to maturity of any given option actually changes on successive days as the maturity date approaches. For o-t-c options, however, new options with standard tenors are issued each day, making it possible to have a time series of option prices with a fixed tenor. Another advantage of option prices is that they are based on market participant behavior. This can be contrasted to say, surveys, which are based on what market participants say.

With regard to o-t-c market quoting conventions, first, option prices are quoted in terms of implied volatility. The implied volatility is the value of σ that, given all the other parameters, will result in the observed market price of the option. Given the values of the other parameters,there is a 1-1 relationship between the volatility parameter in the Black-Scholes call pricing formula. This 1-1 relationship means option prices can be quoted in terms of currency units or in terms of implied volatility. The use of the Black-Scholes implied volatility does not, however, mean that practitioners believe all the assumptions underlying the Black-Scholes model to be true. Sample FX market quotations can be found in table (1.1B).

A second FX option market quoting convention is the use of the call delta rather than the exercise price as a measure of the moneyness of a call option. The delta of an option is the rate of change of the price of option with respect to change in the price of the underlying asset (i.e. $\delta = \frac{\partial C}{\partial S}$). Castagna (2010) point out that using the delta as a measure of moneyness allows the traders to not worry about small movements of the underlying market during the bargaining process. The delta of a call option is always positive and strictly between 0 and $e^{-r^f \tau}$. Using put-call parity it can the delta of a put option is always negative and strictly between -1 and $(e^{-r^f \tau} - 1)$. The market convention when describing the delta of an option is to ignore the negative sign for put options and express the delta as a percentage. For example, a call option with a delta of 0.10 is a "10δ call ", while a put option with a delta of -0.1 is a "10δ put".

A third o-t-c market quoting convention is that currency options are traded in combinations, with the most being straddles, strangles and risk reversals. For a given time to maturity, a straddle is constructed by going long on an at-the-money call and an at-the-money put option. The profit diagram for a straddle combination strategy is shown in figure (2.1a). Figure (2.1a) strategy illustrates that this strategy will be profitable if there is movement in the price of the underlying asset in any direction. For this reason, the straddle price can be intuitively interpreted as a short cut indicator of the market's perception of the volatility of the underlying spot exchange rate at the time to maturity under consideration.

A risk reversal is obtained when an investor goes long a call option and simultaneously goes short on a put option with the same exercise price. The profit diagram for owning a risk reversal strategy is shown in figure (2.1b). As can be seen in figure (2.1b), the risk reversal strategy is only profitable if the price of the underlying asset moves in a particular direction, and makes a loss if the price moves in another direction. The price of a risk reversal can therefore be interpreted as a short cut indicator of the market's perception on the skewness of the future distribution of the underlying asset. It is noteworthy that since risk reversal quotes are the differences between two implied volatilities, the quoted implied volatility of a risk reversal can be negative. Negative risk reversal quotes can be seen in the sample implied volatilities in table (2.1b). The most commonly traded risk reversal in the o-t-c FX market is the 25δ risk reversal, whereby the call and put used to construct the risk reversal are both 25δ.

A strangle is obtained by going long on an out-of-the-money call and an out-of-the-money put with the same strike price. The profit diagram for a strangle strategy is shown in figure (2.1c). As can be seen from figure (2.1c), the strangle strategy is profitable if there are large movements in either direction in the price of the underlying price. The price of a strangle strategy can therefore be intuitively interpreted as a short indicator of the market's perception regarding the kurtosis of the distribution of future spot exchange rates. To go long on a Vega-Weighted Butterfly (VWB), one sells an at-the-money straddle and buys a symmetric strangle. The pay-off diagram for going long on a VWB is shown in figure (2.1d). While the profit or loss to the previous three contracts can be unlimited, there is an upper bound to the profit or loss that can be obtained from a VWB.

1.3 Information Content of Volatility Surface

The volatility surface is a map of market-quoted implied volatilities for options struck at different prices and expiring at different dates. The volatility surface for a given currency pair contains two sources of information about the market's perception about the future dynamics of the exchange rate. There is information in the map of implied volatilities struck at different prices but same time to maturity (" volatility smile") and information from prices of options with same strike prices but different times to maturity. ("term structure of option prices"). Additionally, if we consider the volatility surfaces for multiple currency pairs, a third source of information, option-implied correlation, can be analyzed. Figure (1.3a) shows an example of a volatility surface.

1.3.1 Volatility Smile

Volatility smile refers to a plot of option-implied volatility at different strike prices. While the volatility surface refers to options with multiple tenors, the volatility smile refers to a single tenor. The right panel of figure (1.3b) shows an example of volatility smile. The empirical existence of a "smile" in the plot of implied volatility against strike prices represents one departure from the Black and Scholes (1973) model, which assumes constant volatility across exercise prices.

Breeden and Litzenberger (1978) show that the following relationship between the call option prices and exercise prices:

$$\frac{\partial^2 C}{\partial K^2} = e^{-r^d \tau} \pi_t^Q (S_T). \tag{1.3.1}$$

In equation (1.3.1), $\pi_t^Q(S_T)$ is the risk-neutral probability density function (pdf) of future spot rates, which captures information about market expectations and preferences. The relationship in equation (1.3.1) implies that in principle, we can estimate the whole pdf of time T spot exchange rate from time t volatility smile. Furthermore, although market participants can be treated as if they are risk-neutral for the purpose of option-pricing, option prices theoretically contain information about both investors beliefs and their risk preferences. This fact can be illustrated using the following expression for the price of a European-style call option:

$$C(t,K,T) = \int_K^\infty M_{t,T}(S_T - K)\pi_t^P(S_T)dS_T = e^{-r^d\tau}\int_K^\infty (S_T - K){\pi_t}^Q(S_T)dS_T. \quad (1.3.2)$$

In equation (1.3.2), $M_{t,T}$ is the investors' stochastic discount factor and $\pi_t^P(S_T)$ is the physical probability density function of future spot exchange rates. The physical and risk-neutral probability densities of future spot exchange rates are related by the following equation:

$$\pi_t^Q(S_T) = e^{r^d\tau}M_{t,T}\pi_t^P(S_T). \quad (1.3.3)$$

Equation (1.3.3) illustrates that information about both investors beliefs ($\pi_t^P(S_T)$) and preferences ($M_{t,T}$ is embedded in the extracted option-implied the risk-neutral probability density.

A forward contract can be viewed as a European-style call option with an exercise price of zero. The theoretical forward exchange rate is given by the formula:

$$F_{t,T} = e^{-r^d\tau}\int_0^\infty S_T\pi_t^Q(S_T)dS_T \quad (1.3.4)$$

Evaluating equation (1.3.2) at $K = 0$ yields:

$$C(\tau, 0) = e^{-r^d\tau}\mathbb{E}_t^Q(max(S_T - K, 0)) = e^{-r^d\tau}\int_0^\infty S_T\pi_t^Q(S_T)dS_T = F_{t,T}. \quad (1.3.5)$$

Therefore, for a given tenor, the volatility smile conceptually contain information about market expectations beyond that contained in a forward contract.

1.3.2 Term Structure of FX Option Prices

Prices of options with same strike prices but different maturities potentially provide a second source of information about the markets expectations of evolution of spot exchange rates and the markets perception of risk. A non-flat term structure of implied volatility represents another departure from the Black-Scholes model, which assumes that volatility is constant and the same for all tenors. The left panel of figure (1.3b) shows an example of volatility smile.

"Expectation Hypothesis" for Implied Volatility

For interest rates, the expectation-hypothesis is the theory that the return from holding successive short-term deposits should on average the return from holding a single long term deposit. Under the expectation hypothesis for interest rates, the slope of the yield curve is a good indicator of expected future short term rate.

Extending the expectation hypothesis to implied volatility, the expectation hypothesis holds if the current implied volatility for long term options is consistent with the current and future short-dated implied volatility. For example, if the current nine month implied volatility is 15% and the current three month volatility is 10%, then, according to the expectation hypothesis, the six month implied volatility three months should be 16.96%. This is because:

$$0.75(0.15)^2 = 0.25(0.1)^2 + 0.5(0.1696)^2$$

Even if the hypothesis does not hold empirically, it might still be the case that the current spread between long term implied volatility and short term implied volatility might still provide some predictive power for future short term implied volatility.

1.3.3 Option-Implied Measures of Comovement

Option-implied correlations arise from three way arbitrage arguments. For example: if the exchange rates at time t are given by $S_{AB,t}$, $S_{AC,t}$ and $S_{BC,t}$ and assuming they follow stationary processes, we have :

$$ln(S_{AB,t}) = ln(S_{AC,t}) - ln(S_{BC,t}) = s_{AC,t} - s_{BC,t} \tag{1.3.6}$$

The equation above implies that:

$$Var(s_{AB}) = Var(s_{AC}) + Var(s_{BC}) - 2\rho(s_{AC}, s_{BC})\sqrt{Var(s_{AC})}\sqrt{Var(s_{BC})}. \qquad (1.3.7)$$

This can be rearranged to give:

$$\rho(s_{AC}, s_{BC}) = \frac{(Var(s_{AC}) + Var(s_{BC}) - Var(s_{AB}))}{2\sqrt{Var(s_{AC})}\sqrt{Var(s_{BC})}} \qquad (1.3.8)$$

If we use option-implied variance to estimate the right hand side of equation (1.3.8), then the resulting estimate of $\rho(s_{AC}, s_{BC})$ is option-implied correlation. Siegel (1997) points out that option-implied correlations reveal market sentiments regarding how closely the currencies are expected to move in the future.

In addition to the option-implied correlation, which measures linear codependency, one can also potentially extract option-implied measures of higher moment codependency such as option-implied co-skewness and option-implied co-kurtosis.

1.3.4 FX Options and Exchange Rate Economics: Literature Review

I give an overview three strands of literature that use a subset of FX volatility surface or can be extended to FX option price data and empirical techniques. First, there are studies that use information contained in either the FX volatility smile, term structure of option prices and FX option-implied correlations to address questions in the economics of exchange rates. Second, there are studies that use term structure of FX forward contracts and term structure of interest rates to study exchange rate dynamics. These studies can be extended to option prices, given that conceptually, given that forward contracts are options with a strike price of zero. Lastly, I review studies in which the analysis was done using options with a different underlying asset, and discuss how the analysis can be extended to FX options.

FX Options Volatility Smile

Using overnight FX option prices, Grad (2010) links foreign exchange risk premium to macroeconomic risk by investigating the behavior of FX option prices around US and foreign macroeconomic announcements. He finds that the entire risk neutral distribution of FX options moves significantly due to anticipated and recent macroeconomic news announcements. Grad (2010) interprets these finding as suggesting that a component of the FX risk premium can be explained as compensation for macroeconomic risk.

Aydin et al. (2010) use o-t-c 1 month currency option price data for the Turkish Lira-USD exchange rates. They use the Malz (1997) methodology to extract option-implied risk neutral densities and study the time series evolution of market sentiment over possible values of future exchange rates. They study the extracted densities on selected days during the financial crisis period of 2007-2008. They highlight an increase in uncertainty (wider densities) during days of financial turbulence. They also find shrinking densities after policy announcements, suggesting that the policy measures were credible/effective.

Gereben (2002) uses 1, 2, 3, 6, 9 and 12 month o-t-c NZD/USD option prices to quantify market expectations of future exchange rate uncertainty. He finds that the extracted option-implied probability distributions provide crucial insights about market's expectations of future exchange rate risk. He also finds that option-implied moments can explain the forward premium found in the NZD/USD exchange rate. Gereben (2002) used the Malz (1997) method to extract option-implied risk-neutral distributions.

Csavas (2008) estimate risk-neutral probability density functions from EUR/HUF currency options using the Malz (1997) method. He first compares different options-based indicators and present various "short-cut" indicators. Csavas (2008) finds that option-implied risk-neutral distributions do not provide accurate forecasts of the historical EUR/HUF exchange rate, and that higher moments of risk-neutral densities responsible for rejection. He also finds that the option-implied higher order moments are able to explain a huge variation of the estimated foreign exchange rate risk premium. He interprets these findings as suggesting that the risk-neutral standard deviation, skewness and kurtosis can be used as proxy variables for the central moments of the subjective densities.

Castren (2005) use FX option price data for three EU member countries (Poland,Czech Republic and Hungry) against the EURO and the USD. He estimates risk-neutral density functions and density interval bands. He analyzes the movements of these densities around monetary policy announcements.

Term Structure of Option Prices

Mixon (2007) tests the expectations hypothesis of the term structure of implied volatility using several market indexes. The tests indicate that the slope of at-the-money implied volatility over different maturities has predictive ability for short-dated implied volatility.This predictive ability is however, not as high as that predicted by the expectation hypothesis. Mixon (2007) may be due to failure to control for risk premium in the prices of options.

Byoun et al. (2003) use a stochastic volatility option pricing model to show that the implied volatilities of at-the-money option are not unbiased. Their results do not support the expectation hypothesis, and their results are similar for both FX and S&P 500 stock options.

Campa et al. (1998) use daily o-t-c FX option price data for the USD against the Pound, Mark, Yen and Swiss Franc, and they are unable to reject the expectation hypothesis in most of the cases. They also find no evidence of systematic overreactions of the long rate implied volatility to changes in corresponding short rates. The findings by Campa et al. (1998) are in contrast to those of Stein (1989), who finds evidence of overreactions for options on S&P500 index.

Term Structure of FX forward prices

As noted in subsection (1.3.1), forward contracts can be viewed as options with strike price of zero. While the forward rate has been shown to be a biased predictor of future spot rate, Clarida and Taylor (1997) and Clarida et al. (2003) show that the term structure of forward premia has some predictive power. Sarno and Valente (2005) extend the analysis to density forecasting, and show that the term structure of forward premia performs well in forecasting future exchange rate densities.

Chen and Tsang (2013) show that the term structure of relative rate interest rates have predictive power for nominal exchange rates.

This relatively good performance of the term structure of forward premia in forecasting exchange rates further motivates studying the information content of the term structure of volatility smiles. (i.e. the volatility surface).

Option-Implied Codependencies

Campa and Chang (1998) find that for the purpose of forecasting 1 month and 3 month realized correlation, option-implied correlation out-performs historical correlation, exponentially weighted moving average correlation and correlation estimated using a GARCH(1,1) model.

Walter and Lopez (2000) find that for the USD/DEM/JPY currency trio, implied correlation are useful for forecasting the observed correlation, but do not incorporate all the information contained in historical correlation, but do not incorporate all the information contained in historical correlations. They however, find that for the USD/DEM/CHF trio implied correlations are much less useful.

Brinkmann et al. (2014) develop option-implied measures of higher order dependencies between assets, and show that portfolios constructed using option-implied covariance, co-skewness and co-kurtosis matrices significantly outperforms portfolios constructed using matrices from historical data.

1.3.5 Extracting Option-Implied Densities and Moments: A Review

Risk-neutral probability distributions are important because they allow any derivative of the underlying asset and with the same time to maturity to be priced. Furthermore, by exploiting the relationship between risk-neutral density functions and the economy's stochastic discount factor highlighted in equation (1.3.3), extracted risk-neutral distributions can be used to get estimates of the physical distribution of future exchange rates. These physical distributions can in turn be used for forecasting future exchange rates.

In this section I review methods of extracting option-implied distributions and their moments and discuss some practical issues in the interpretation and econometric analysis of these moments.

Castagna (2010) proposes three criteria for selecting a representation of the volatility surface: parsimony, consistency and intuitiveness. The parsimony criterion postulates that the representation of the volatility contains the smallest amount of information needed to retrieve the entire volatility surface. The consistency criterion says that information contained in the representation be along strike prices in a way that makes integration of missing points easily possible. Lastly, the intuitiveness criterion states that each piece of information distinctly affects one specific characteristic of the volatility surface.

Bahra (1997) classifies the methods for extracting option-implied risk neutral densities into four categories:

- methods that make assumptions assumptions regarding the stochastic process followed by the underlying asset's price,
- methods that make parametric assumptions the risk neutral distribution function,
- methods that start by making a parametric specification of the call price function
- non-parametric methods, which make no assumptions on either the call pricing function, the risk neutral density funtion or the stochatic process followed by the underlying asset's price.

Challenges in the empirical analysis of FX option prices

While FX options theoretically contain information useful for understanding exchange rate dynamics, there are several challenges. First, options are observed at a daily frequency, while the econometric analysis is for longer frequencies. This means we have to use econometric methods for overlapping observations.

Another empirical challenge that comes with o-t-c is the relative lack of transparency when compared to exchange traded options. For example, there is no clear information on volume of o-t-c options traded. There are also liquidity problems for FX options of currencies of developing countries.

1.4 FX Options During the Financial Crisis

As argued in section (1.3.5), option prices theoretically contain information over and above that contained in the spot an interest rate markets, as they reflect the market's perception of the uncertainty surrounding future exchange rate developments. Because of their forward-looking property, currency options are a good source for monitoring existing market sentiment. Assessing the accuracy of the sentiment contained in currency options is, however, an empirical question.

In this section, I investigate the developments of option-implied measures of risk during the financial crisis of 2008. In particular, I study whether there are any noticeable movements in option-implied moments around some major macroeconomic and market events during this time. The time line of events that we consider is given in table (1.4).

1.4.1 Data Description

We use o-t-c FX option price data for the currency pairs listed in table (1.1A), covering the period 1 January 2007 to 31 December 2008. Our data consists of at-the-money straddles, 25δ vega-weighted butterflies and 25δ risk reversal with times to maturities of 1 week, 1 month, 2 months, 3 months and 6 months. Sample option prices are shown in table (1.1B).

For each of the currency pair and tenor, we extract option-implied standard deviation, skewness and kurtosis of the distribution of $ln\left(\frac{S_{t+1}}{S_t}\right)$ using the methodology of Bakshi et al. (2003a). The time series evolutions of extracted moments moments are shown in the plots in figure (2.2).

During the same period of Jan 1 2007 to Dec 31 2008, we also document some major market events government actions and federal reserve actions. The goal here is to link the dynamics of option-implied moments with macroeconomics events. Table (1.2) contains the events that we consider. The dates that are in bold are the ones we plot in the time series plots shown in figure 1.5. Full timeline of events can be found in figure (1.4).

Early to Mid 2007

In the time series plots in figure 1.5, the first vertical bar corresponds to 24 January 2007, when the largest home price in 25 years was experienced. The second bar corresponds to March 16 2007, when Bear Stearns was sold to JP Morgan Chase.

Looking at the time series plots of option-implied moments before, between and after these two events, for the most part, there was no huge movements in the option-implied standard deviations during this period, as can be seen in the figures 1.5a, 1.5d, 1.5g, 1.5j, 1.5m. On the USDJPY plots, option-implied moments appear to go up in the period between January 24$^{\text{th}}$ and March 16$^{\text{th}}$. All the plots show a clear term structure pattern, with annualized option-implied standard deviations positively correlated with the time horizon.

Looking at the option-implied skewness plots, we generally see a term structure pattern in the levels. Again, there is no clear fluctuation of the skewnesses before, between and after these two dates. There is, however, an increase in the skewness for the USDJPY currency pair in the period leading to the January 24$^{\text{th}}$ sharp drop in house prices. Furthermore, there is no clear term structure pattern for USDJPY before Jan 24$^{\text{th}}$ 2007.

Mid 2007 to Mid 2008

There are some jumps in kurtosis around periods of some market events in October 2007 and November 2007, with the most prominent one corresponding the November 10 lobby for auto-industry bailouts. For example 1.5i and 1.5m.

Mid 2008 to Late 2008

The period between mid 2008 to and of 2008 is dominated by government and Federal Reserve actions to stabilize the economy. However, the option-implied standard deviations for all times to maturity. One way to interpret this phenomenon is that the market's perception of whether these stabilizing actions would work within a specified timeline was not positive; market participants had no confidence it would work within a week, a month, 6 months, depending on the tenor.

FX Options and the Financial Crisis: Concluding Remarks

Option-implied moments can theoretically be used to gauge market sentiment regarding the time series evolution of exchange rates (market events) as well as the effectiveness and credibility of monetary and government policy actions.

A financial crisis period such as 2007-2008 provide a good natural experiment for analyzing the link between macroeconomic events and option-implied moments because of the market events and government and monetary policy actions. However, financial option prices are also characterized by high fluctuations and outliers, making it harder to get generalized information from option prices.

1.5 Conclusion

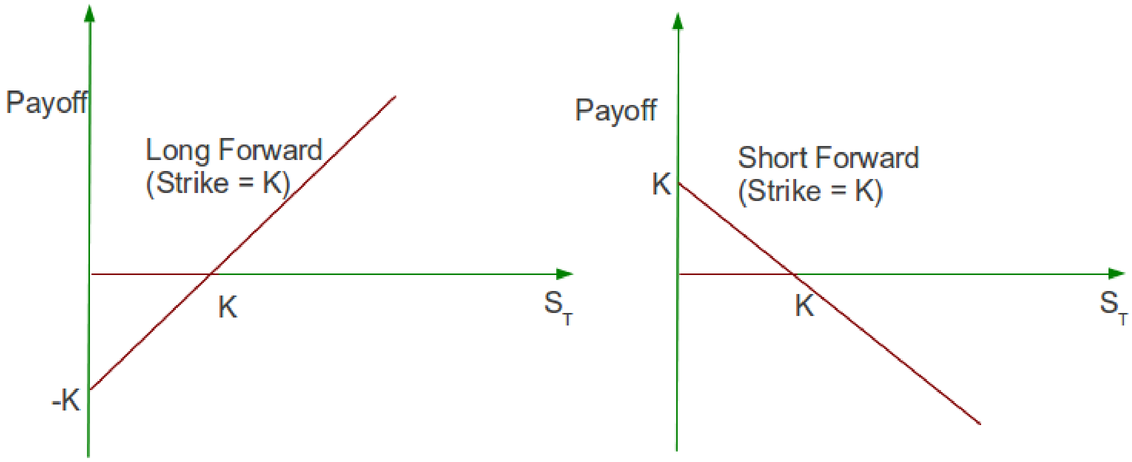
In this Chapter, I have argued for the joint study of FX option pricing and the economics of exchange rates, further bridging the gap that has existed historically between these two strands of literature. I use this Chapter to introduce some of the terminology and conventions used in the FX options markets, which is useful for doing research in this interdisciplinary strand of literature. I also give an overview of three potential sources of market-based information from currency options: volatility smile, term structure of implied volatility and option-implied measures of co-dependence such as correlation, co-skewness and co-kurtosis. I also give a brief overview of the empirical methods for extracting option-implied measure of risk such as standard deviation, skewness and kurtosis from the price of currency option.

Finally, I illustrate an example of empirically linking FX option-implied measures of risk by investigating the correlation between FX option-implied moments and macroeconomic market and government events during the financial crisis period of 2007-2008. Over the years, the empirical link between asset prices and macroeconomic events have been difficult to uncover, despite economic theory predicting that the asset prices are determined by macroeconomic variables such as output and inflation. Option-prices and option-implied moments provide market-based and forward-looking data that can be used to investigate the empirical relationship between exchange rates and macroeconomic variables and events.

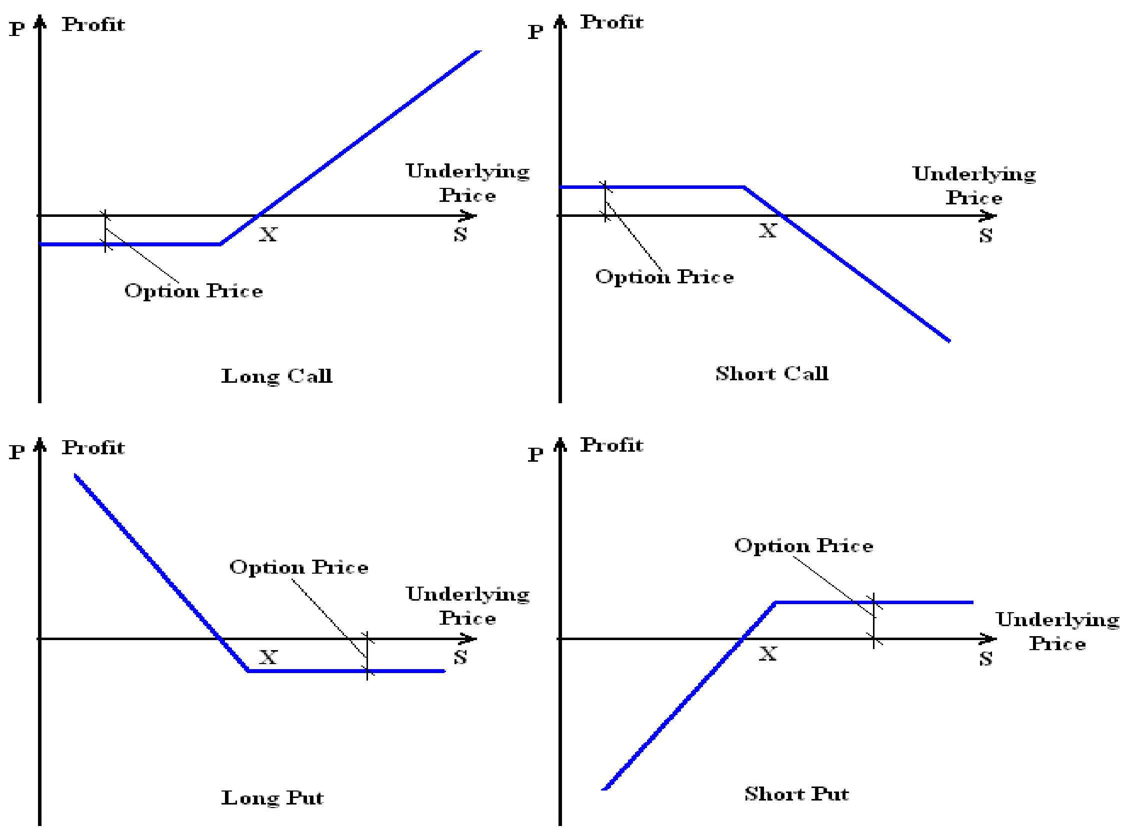
The rest of the dissertation proceeds as follows. In chapter two I show that the term structure of FX option-implied measures of risk explain exchange rate dynamics as well as exchange rate excess returns. These findings suggest that expectations and risk are crucial for explaining exchange rate dynamics. In chapter three, I revisit one of the well known empirical puzzle in exchange rate economics, the uncovered interest parity puzzle. I argue that standard ways of testing the UIP hypothesis are non-informative since they tend to impose auxiliary assumptions. I then propose options-based approaches to testing the hypothesis that may be more informative.

Figure 1.1: Profit diagrams for plain vanilla options

(a) Profit diagrams for a forward contracts



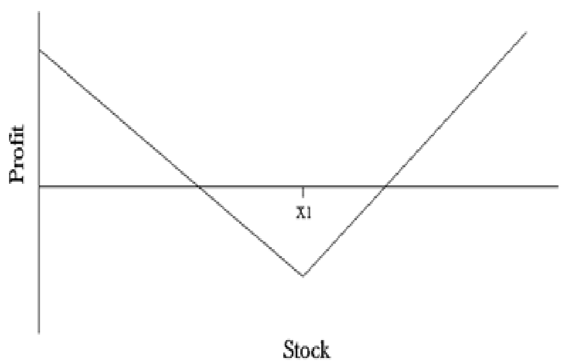
(b) Profit diagrams for Call and Put Option Contracts



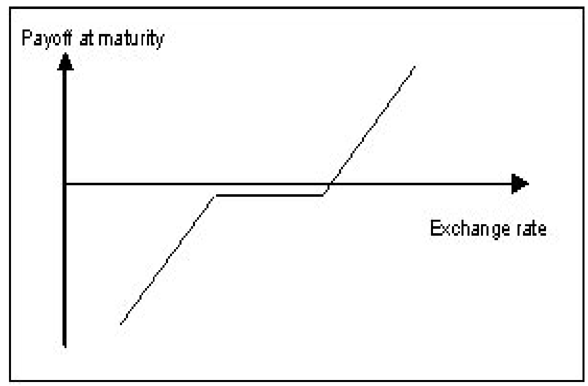
Note:Payoff diagrams of the plain vanilla derivative contracts introduced in section (1.2)Pay-offs/Profits from forward contracts are linear functions of the spot price, while pay-offs to options are nonlinear.

Figure 1.2: Profit diagrams of commonly traded FX option strategies

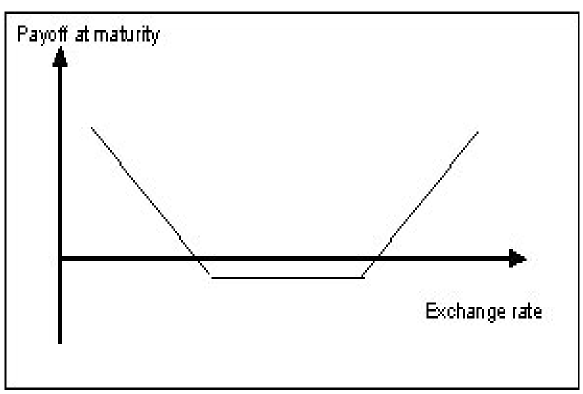
(a) Profit Function of a Straddle



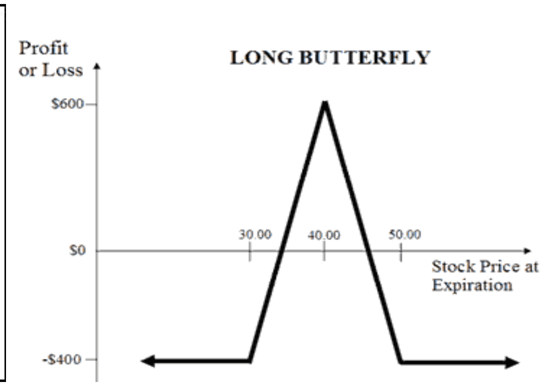
(b) Profit Function of a Risk Reversal



(c) Profit Function of a Strangle



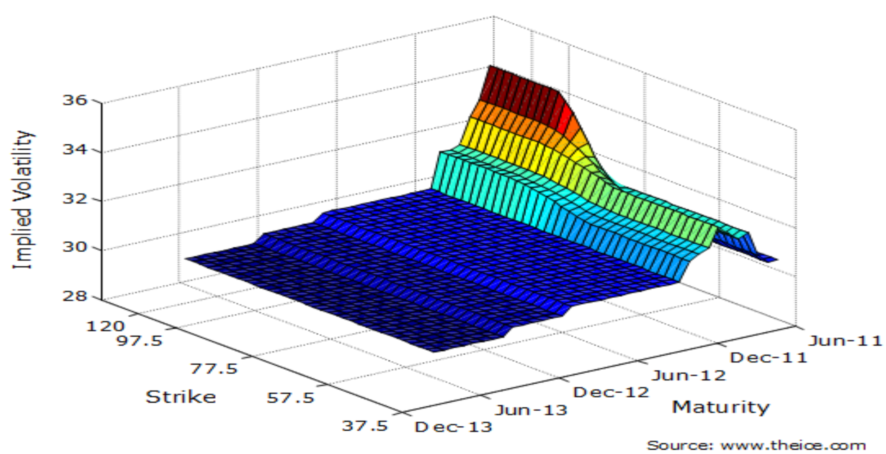
(d) Profit Function of a Butterfly



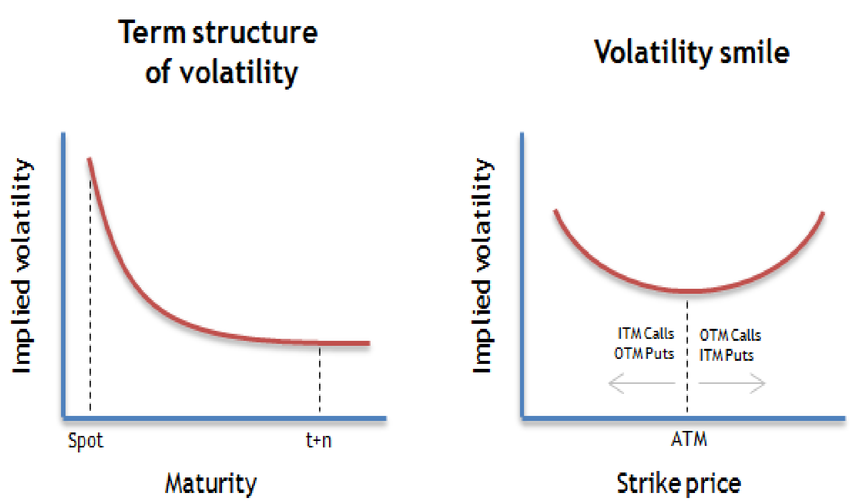
Note: Straddle,Risk Reversal,Strangle and Butterfly are as defined in subsection (1.2.2)

Figure 1.3: Implied Volatility Surface example

(a) Volatility Surface



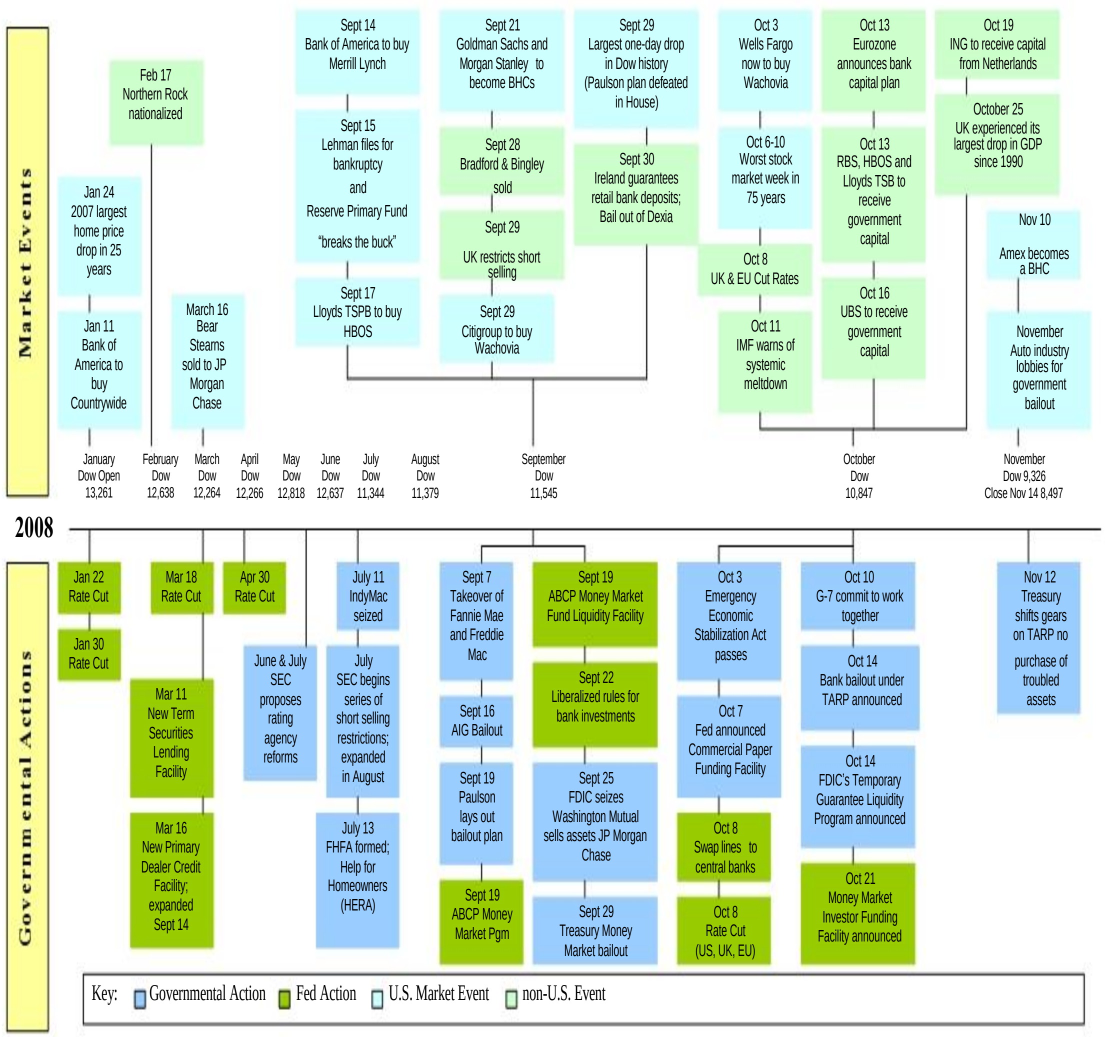
(b) Term Structure of Implied Volatility and Volatility Smile



Note:This is an implied volatility surface.

Figure 1.4: Financial Crisis Timeline:2008

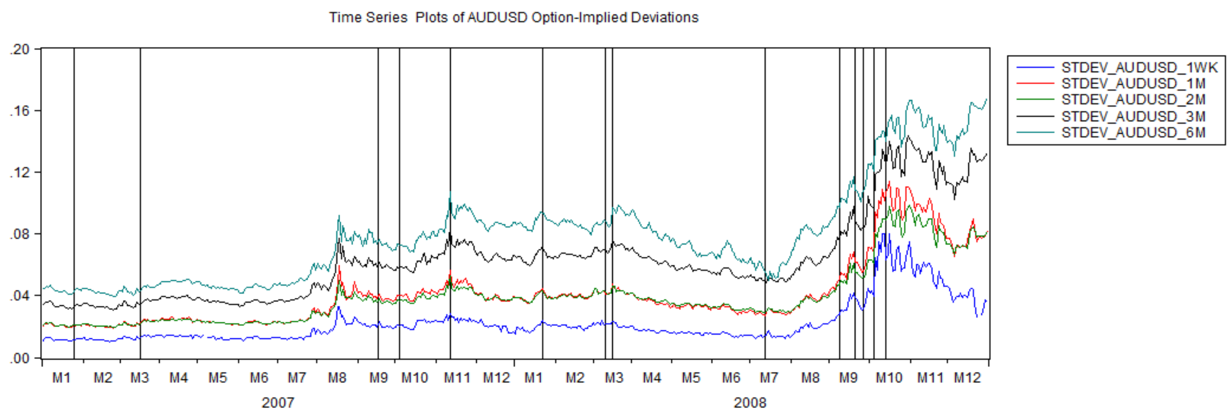
(a) Financial Crisis Timeline



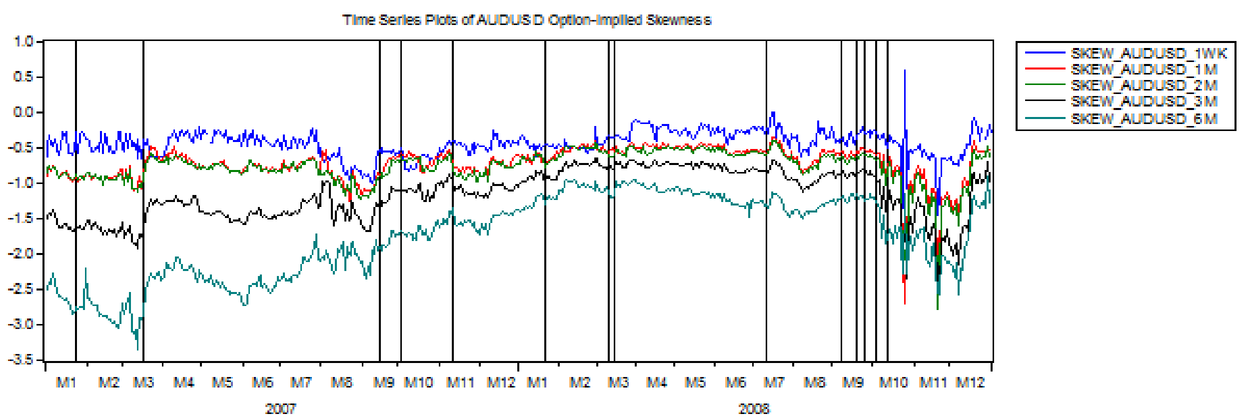
Note:

Figure 1.5: Time Series Evolution Of option-implied Moments

(a) AUDUSD STDEV



(b) AUDUSD SKEWNESS



(c) AUDUSD KURTOSIS

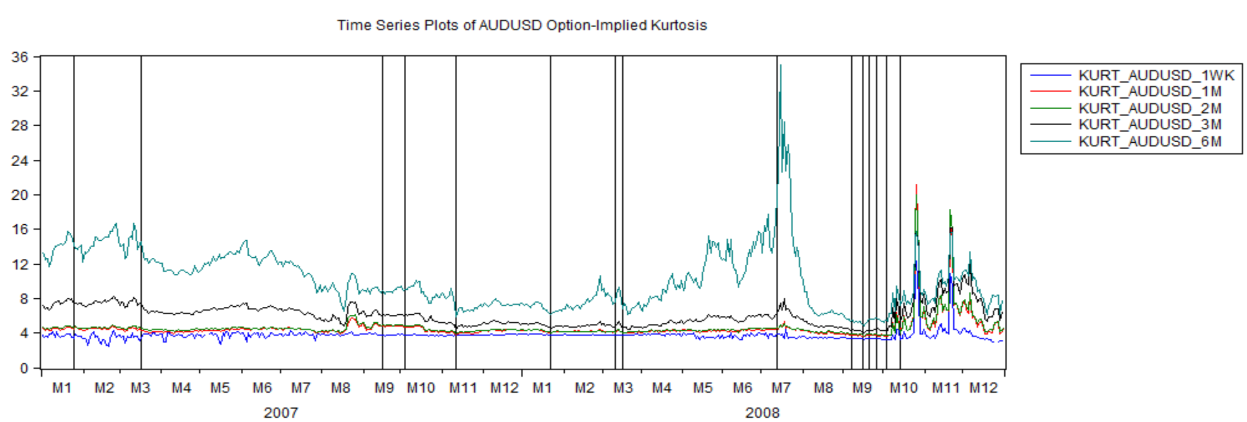
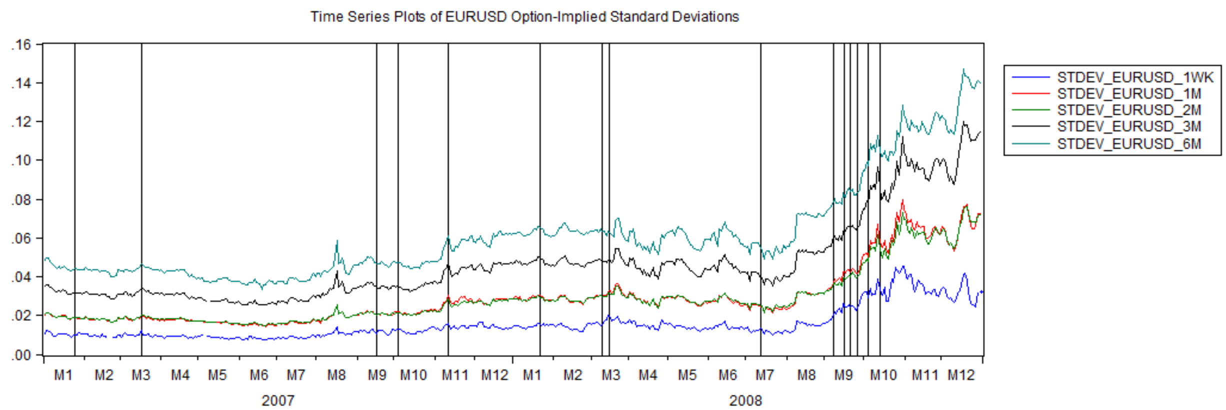
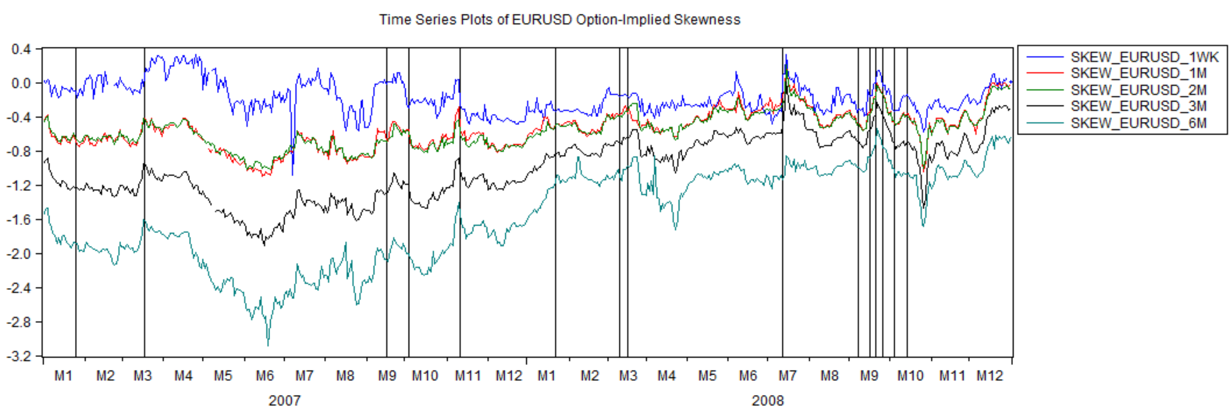


Figure 1.5: Time Series Evolution Of option-implied Moments

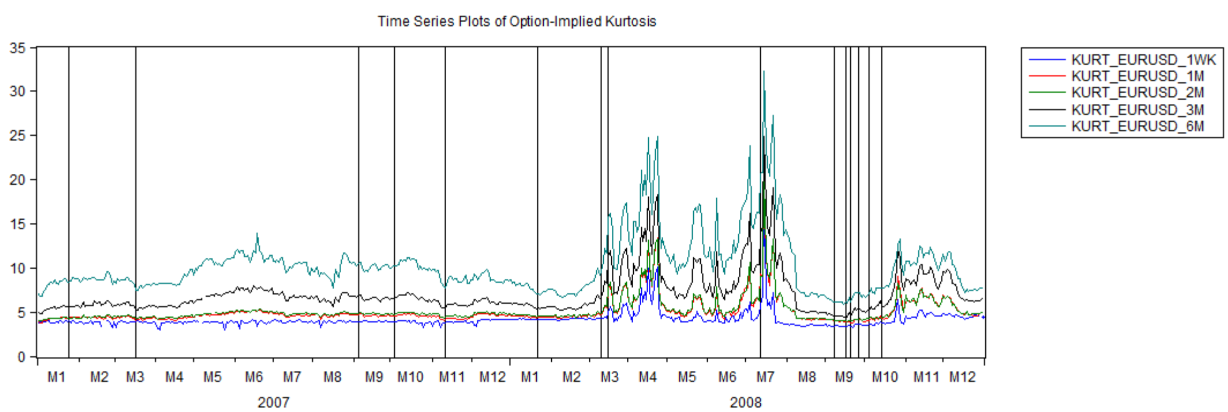
(d) EURUSD STDEV



(e) EURUSD SKEWNESS



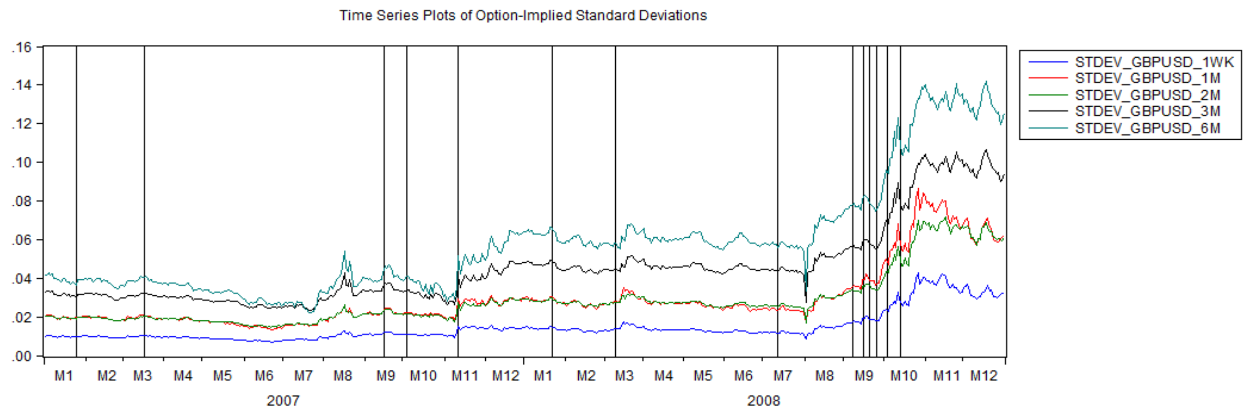
(f) EURUSD KURTOSIS



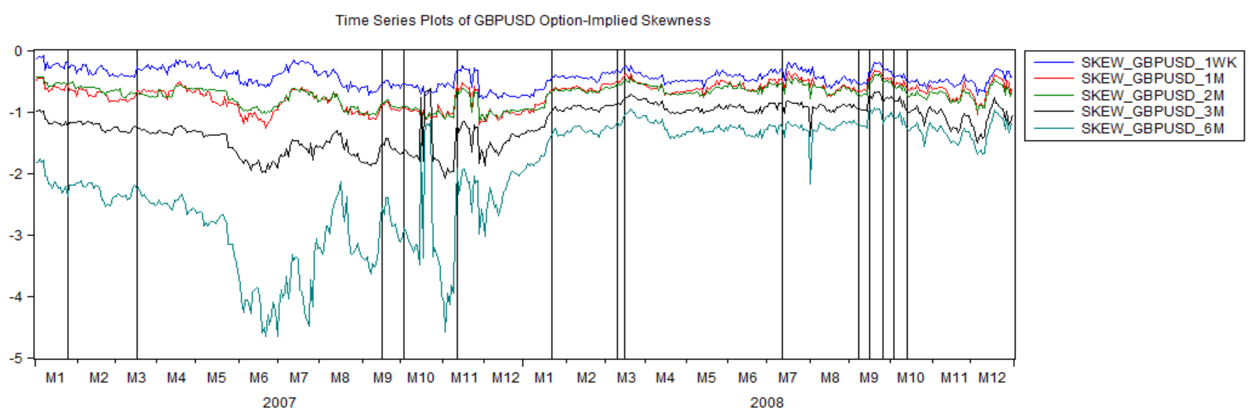
Note: Moments extracted using the methodology developed in Bakshi et al. (2003a).

Figure 1.5: Time Series Evolution Of option-implied Moments

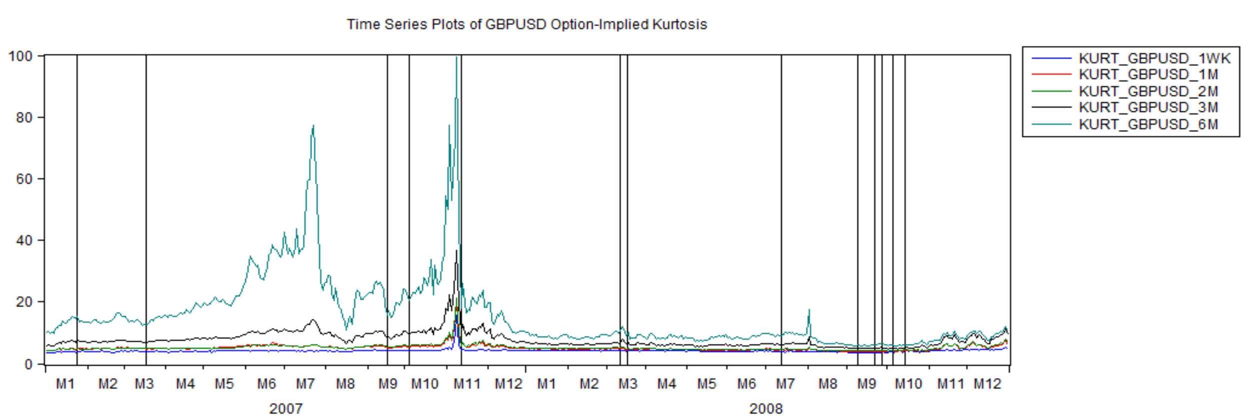
(g) GBPUSD STDEV



(h) GBPUSD SKEWNESS



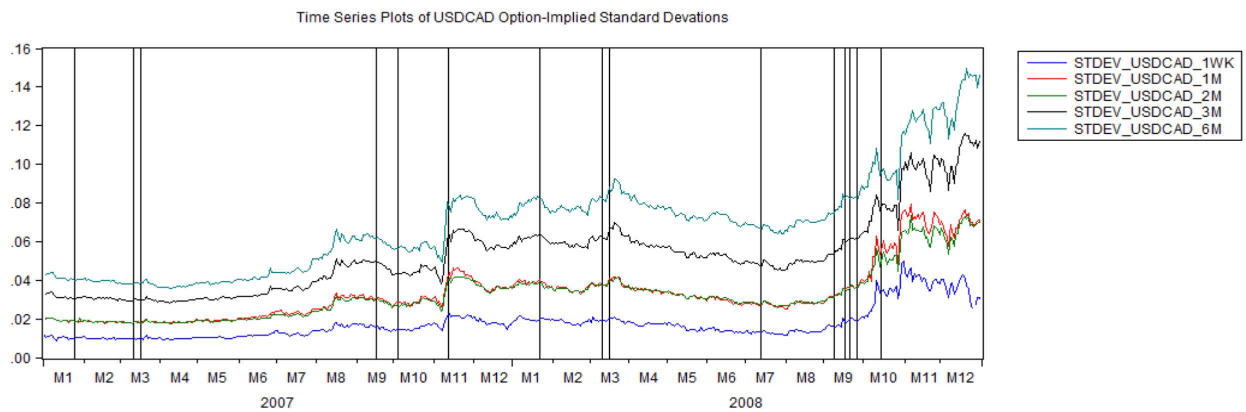
(i) GBPUSD KURTOSIS



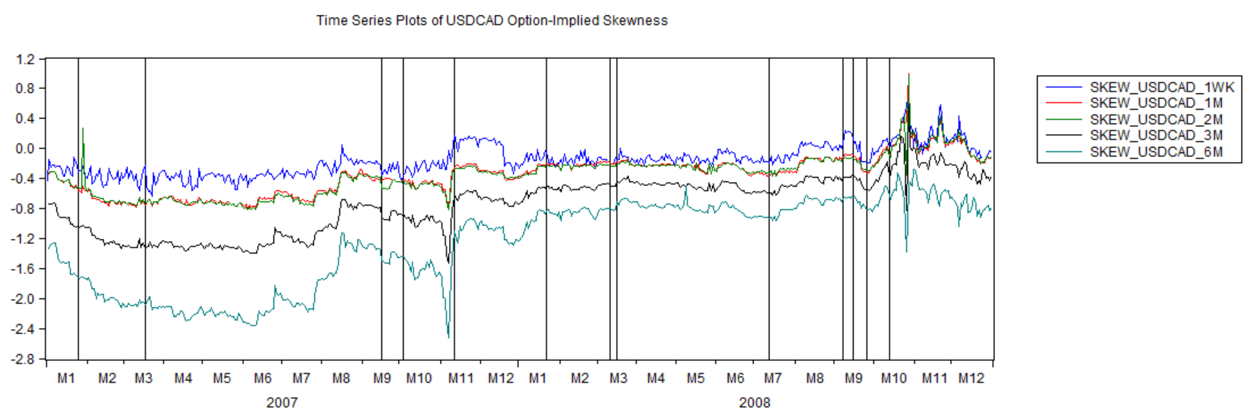
Note: Moments extracted using the methodology developed in Bakshi et al. (2003a).

Figure 1.5: Time Series Evolution Of option-implied Moments

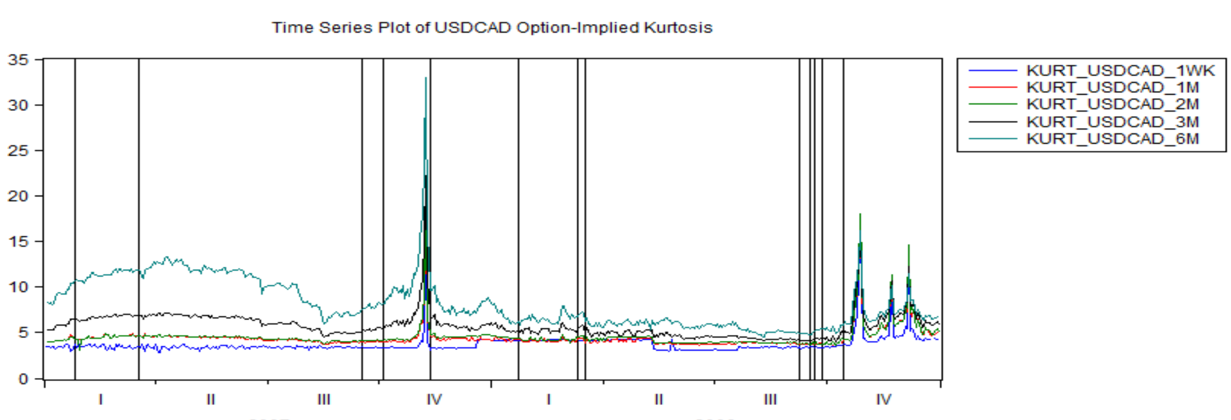
(j) USDCAD STDEV



(k) USDCAD SKEWNESS



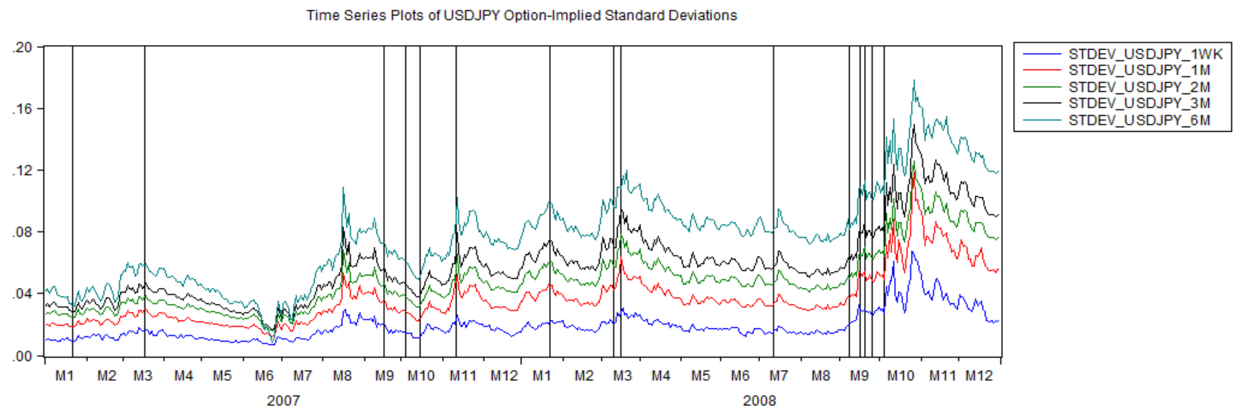
(l) USDCAD KURTOSIS



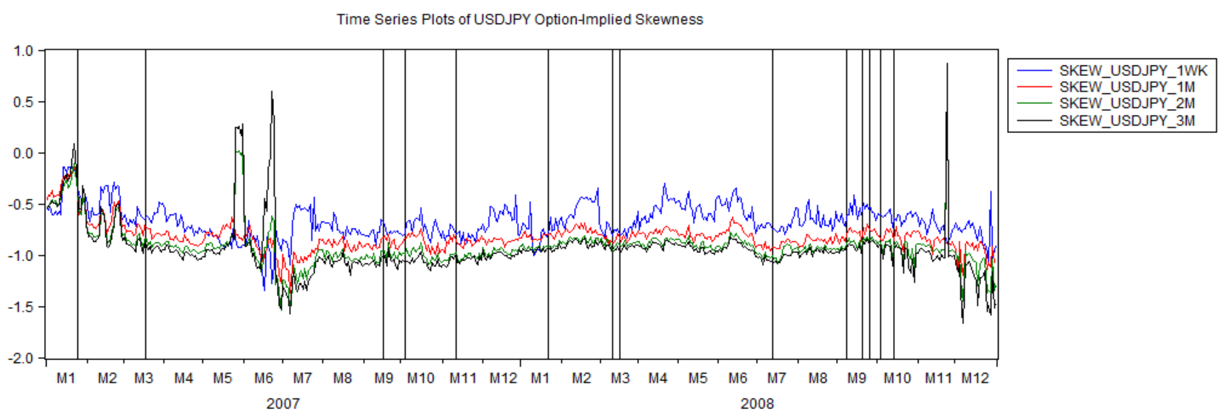
Note: Moments extracted using the methodology developed in Bakshi et al. (2003a).

Figure 1.5: Time Series Evolution Of option-implied Moments

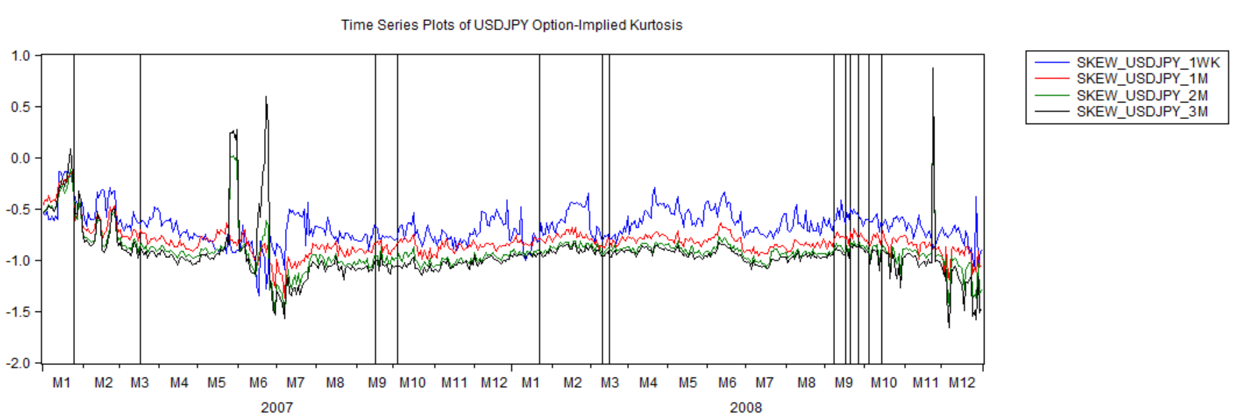
(m) USDJPY STDEV



(n) USDJPY SKEWNESS



(o) USDJPY KURTOSIS



Note: Moments extracted using the methodology developed in Bakshi et al. (2003a).

Table 1.1: O-T-C Market Statistics and Conventions

A. Quoting Conventions in o-t-c FX Options Market

Symbol	Definition	Base currency	Domestic currency	Positive Skew means
AUDUSD	USD per AUD	AUD	USD	USD depreciation
EURJPY	JPY per EUR	EUR	JPY	EUR depreciation
EURUSD	USD per EUR	EUR	USD	USD depreciation
GBPUSD	USD per GBP	GBP	USD	USD depreciation
USDCAD	CAD per USD	USD	CAD	CAD depreciation
USDJPY	JPY per USD	USD	JPY	JPY depreciation

B. Sample Annualized Implied Volatilities

Tenor	ATM	25D RR	25D VWB	10D RR	10D VWB
1 Week	7.352	-0.495	0.131	-0.847	0.379
1 Month	6.851	-0.347	0.136	-0.584	0.389
2 Month	6.851	-0.366	0.157	-0.619	0.449
3 Month	6.851	-0.396	0.162	-0.663	0.485
6 Month	6.901	-0.426	0.187	-0.703	0.54
9 Month	7.051	-0.446	0.197	-0.743	0.571
12 Month	6.901	-0.426	0.187	-0.703	0.54

C. Average Daily Turnover in FX market (billions)

	1998	2001	2004	2007	2010	2013
Spot FX Transactions	568	386	631	1005	1488	2046
Percentage Change	N/A	-32	63.5	59.3	48.3	37.5
FX Derivatives						
Outright Forwards	128	130	209	362	475	680
FX Swaps	734	656	954	1714	1759	2228
Options and other products	**87**	**60**	119	**212**	**207**	**337**
Percentage Change	N/A	-31	98.3	83	-2.4	62.8
Exchange Traded Derivatives	11	12	26	80	155	160

Note: "ATM" is at-the-money straddle, 25D RR and 10D RR are 25%- and 10%- delta risk reversals respectively; and 25D VWB and 10D VWB are 25%- and 10%- delta Vega-weighted butterflies respectively. See Section (3.3.1) for more details. The numbers in table (3.1C) are from Bank of International Settlements (2013). In table (3.1C) , "other products" refers to "highly levereged transactions and/or trades whose notional amount is variable and where a decomposition into individual plain vanilla components was impractical or impossible" Bank of International Settlements (2013).

Table 1.2: Selected US Market Events Government/Fed Actions: Jan 1 2007-Dec 31 2008

Date	Type	Event
Jan 24 2007	**Market**	**Largest home price drop in 25 years**
March 16	**Market**	**Bear Stearns sold to JP Morgan Chase**
Sep 14	Market	Bank of America to buy Merryl Lynch
Sep 15	**Market**	**Lehman Brothers files for bankruptcy**
Sep 29	Market	Largest one day drop in Dow history[a]
Sep 29	Market	Wachovia to be bought by Citigroup
October 3	**Market**	**Wells Fargo now want to buy Wachovia**
November 10	**Market**	**Auto industry lobbies for government bailouts**
January 22 2008	**Fed Action**	**Fed cuts rates**
January 30	Fed Action	Further Fed cuts rates
March 11	**Fed Action**	**New term securities lending facility**
March 16	**Fed Action**	**New primary dealer credit facility expanded to September 14**
July 11	**Government Action**	**IndyMac seized**
September 7	**Government Action**	**Take-over of Fannie-Mac and Freddie Mac**
September 16	**Government Action**	**AIG Bailout Plan**
September 19	Government Action	Paulson lays out bailout plan
September 25	**Government Action**	**FDIC seizes WAMU and sells assets to JP Morgan Chase**
October 3	**Government Action**	**Emergency Economic stabilization bill passed**
October 14	**Government Action**	**Banks bailed under TARP announced**
	Government Action	FDIC temporary liquidity program announced

Note:

[a] Paulson plan defeated in house

Chapter 2

UNDERSTANDING EXCHANGE RATE DYNAMICS: WHAT DOES THE TERM STRUCTURE OF FX OPTIONS TELL US ?

2.1 Introduction

The exchange rate economics literature has over the years faced many empirical puzzles. For example, although theory predicts that nominal exchange rates should depend on current and expected future macroeconomic fundamentals, the consensus in the literature is that exchange rates are essentially empirically "disconnected" from the macroeconomic variables that are supposed to determine them. This empirical disconnect comes in the form of low correlations between nominal exchange rates and their supposed macro-based determinants and also in the form of poor performance of macro-based exchange rate models in out-of-sample forecasting.[1]

A related empirical anomaly that has received considerable attention in the literature is the uncovered interest parity (UIP) puzzle or the forward premium puzzle. The UIP puzzle is the empirical irregularity showing that the forward exchange rate is a biased predictor of future spot exchange rates. The UIP puzzle is taken seriously in the exchange rate literature because the UIP condition is a property of most open-economy macroeconomic models.

One manifestation of this empirical (ir)regularity is that countries with higher interest rates tend to see their currencies subsequently appreciate and a "carry-trade" strategy exploiting this pattern, on average, delivers excess currency returns.[2] This violation of the UIP condition is commonly attributed to time-varying risk premia and biases in (measured) market expectations. However, empirical proxies based on surveyed forecasts or standard measures of risk - for instance, ones built from consumption growth, stock market returns,

[1] See Engel (2013) for a review.

[2] A carry trade strategy is to borrow low-interest currencies and lend in high-interest currencies, or to sell forward currencies that are at a premium and buy forward currencies with a forward discount.

or the Fama and French (1993) factors -have been unsuccessful in explaining the puzzle.[3] As such, while recognizing the presence of risk, macroeconomic-based approaches to modeling exchange rates often ignore risk in empirical testing.[4] [5]

This paper argues that the persistent empirical puzzles faced by the exchange rate economics literature are most likely due to overly restrictive preference and distributional assumptions in conventional testing methods. For example, researchers typically assume that exchange rate returns are normally distributed, or that investors' utility functions depend only on the mean and variance. We argue that these auxiliary assumptions often inadequately account for either the forward-looking property of nominal exchange rates or potential skewness and/or fat tails in the distribution of FX returns.

We empirically demonstrate that FX risks as captured by higher order moments of perceived FX returns distributions, as well as expectations, captured by the term structure of option prices, do really matter in explaining exchange rate movements. We highlight the usefulness of capturing risks and expectations in stages. First, we show that options-implied standard deviations, skewness and kurtosis of future exchange rate movements are able to explain not only the conditional mean, but the entire conditional distribution of excess currency returns. Second, we show that information extracted from the term structure of options-implied risk measures add substantial explanatory power for excess currency returns. Finally, we show that quarterly exchange rate movements are well explained by the term structure of 1^{st}-4^{th}moments of options-implied returns distributions, with adjusted R^2s ranging from 58% for USDJPY to 84% for GBPUSD.

Simple derivatives such as forwards and futures have been used extensively in explaining excess currency returns or exchange rate movements.[6] Payoffs from forward contracts,

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[3] See, Engel (1996) for a survey of the forward premium literature, as well as recent studies such as Burnside et al. (2011) and Bacchetta and van Wincoop (2009).

[4] (See for instance, Engel and West (2005); Mark (1995))

[5] On the finance side, efforts aiming to identify portfolio return-based "risk factors" offer some empirical success in explaining the *cross-sectional* distribution of excess FX returns, but have little to say about bilateral exchange rate dynamics (see for example, Lustig et al. (2011); Verdelhan (2012)). Lustig et al. (2011) and Verdelhan (2012) for example, identify a "carry factor" based on cross sections of interest rate-sorted currency returns and a "dollar factor" based on cross sections of beta-sorted currency returns.

[6] See for example, Hansen and Hodrick (1980) and Clarida and Taylor (1997) among many others.

however, are linear in the return on the underlying currency and as such do not contain as useful a set of information as the non-linear contracts we examine. Conceptually, since payoffs of option contracts depend on the uncertain future realization of the price of the underlying asset, option prices must reflect market sentiments and beliefs about the probability of future payoffs.

Our use of options price data and related empirical methodologies has a number of motivating factors. First, options are forward-looking by construction, which means option prices should therefore be able to incorporate information such as forthcoming regime switches or the presence of a peso problem.[7] Second, option prices are deeply rooted in market participant behavior because they are based on what market participants do instead of what they say. Furthermore, cross sections of option prices imply a subjective probability distribution of future spot exchange rates, which captures both market participants' beliefs and preferences.[8] Third, modern techniques such as the Vanna-Volga method [9] and the methodology of Bakshi et al. (2003b) facilitate elegant and model-free computation of options-implied higher order moments of future exchange rate changes.

Our empirical findings in this paper have three implications. First, the exchange rate model based on UIP is not that bad, and we can continue using it in open economy macroeconomic models. However, we need to understand that if we put lognormal shocks, they will not fit well. Quick improvements can be made by controlling for the term structure of higher order moments, which can be obtained from option price data. Second, on the financial side, concepts of risk which depend on only the mean and variance such as the Sharpe ratio for portfolio performance evaluation, perhaps ought to be modified to account for the importance of higher moment risks such as skewness and kurtosis.

---

[7] The peso problem refers to the effects on inferences caused by low-probability events that do not occur in the sample, which can lead to positive excess return.

[8] This distribution is commonly referred to as the "risk-neutral distribution", though it does NOT imply that the distribution is derived under risk-neutrality. On the contrary, it incorporates both the expected physical probability distribution of future exchange rate realization as well as the risk premium, or compensation required to bear the uncertainty.

[9] (See Castagna and Mercurio (2005))

2.2 Why Higher Order Moments and Term Structure?

The first purpose of section (2.2) is to emphasize the role that failure to adequately capture market expectations and perceived risk in the FX market potentially plays in causing both the UIP puzzle and the macro disconnect puzzle. The second purpose is to argue that the term structure of option-implied higher order moments capture both perceived risk and expectations of future macroeconomic conditions. Lastly, we argue that option prices potentially offer cleaner proxies of FX *global risk* which can be useful to the recent strand of literature emphasizing the role of global risk in explaining cross-sections of both currency excess returns and currency returns.

2.2.1 Forward Premium Puzzle and Excess Currency Returns

The efficient market condition for the foreign exchange markets, under rational expectations, equates cross border interest differentials $i_t - i_t^*$ with the expected rate of home currency depreciation, adjusted for the risk premium associated with currency holdings, ρ_t:[10]

$$i_t^\tau - i_t^{\tau,*} = \mathbb{E}_t \Delta s_{t+\tau} + \rho_{t+\tau}. \tag{2.2.1}$$

This condition is expected to hold for all investment horizons τ, with interest rates that are at matched maturities. *Ignoring the risk premium term*, numerous papers have tested this equation since Fama (1984), and find systematical violations of this UIP condition:

$$\begin{aligned} & s_{t+\tau} - s_t = \alpha + \beta(i_t^\tau - i_t^{*,\tau}) + \epsilon_{t+\tau};\, \mathbb{E}_t[\epsilon_{t+\tau}] = 0, \forall\, t, \\ & H_0 : \beta = 1 \end{aligned} \tag{2.2.2}$$

with an estimated $\beta < 0$ and $R^2 s$ that are usually close to zero. This is the so-called uncovered interest rate parity puzzle or the forward premium puzzle (see Engel (1996), for a survey of the literature). To see the connection with forward rates, we note that the covered interest parity condition, an empirically valid no-arbitrage condition, equates

[10] In this paper, we define the exchange rate as the domestic price of foreign currency. A rise in the exchange rate indicates a depreciation of the home currency. However, "home" does not have a geographical significance but follow the FX market conventions. See table (3.1A)

the forward premium $f_t^{t+\tau} - s_t$, with interest differentials. The risk-neutral UIP condition above thus implies that the forward rate should be an unbiased predictor for future spot rate: $\mathbb{E}_t s_{t+\tau} = f_t^{t+\tau}$ or $s_{t+\tau} = f_t^{t+\tau} + u_{t+\tau}$, where $\mathbb{E}_t[u_{t+\tau}] = 0 \,\forall\, t$.

We should next define FX excess returns as the rate of return across borders net of currency movement, and one can see that the UIP or forward premium puzzle can be expressed as a non-zero averaged excess return over time:

$$xr_{t+\tau} = f_t^{t+\tau} - s_{t+\tau} = (i_t^{\tau} - i_t^{\tau,*}) - \Delta s_{t+\tau} = \rho_{t+\tau} + u_{t+\tau} \tag{2.2.3}$$

It is natural then to note that the empirical failure of the risk-neutral UIP condition can be attributable to either the presence of a time-varying risk premium, $\rho_{t+\tau}$, or that expectation error, u_t, may not be i.i.d. mean zero over time. If the distribution of either of these is not mean zero over the time series, empirical estimates of the slope coefficient in regression equation (2.2.2) would likely suffer omitted variable bias or other complications.

2.2.2 Why higher order moments?

We show that in addition to risk neutrality and rational expectations assumptions, the UIP condition also hinges on the rather restrictive auxiliary assumptions that FX returns are i.i.d. normal over time and that investors have constant absolute risk aversion (CARA) utility. The two additional assumptions have the effect of reducing the representative investor's optimal asset allocation problem to a mean-variance optimization problem.

We start with the problem of an investor who, in each period, allocates her portfolio among risky assets with the goal of maximizing the expected utility of next period wealth. In each period, the investor has n risky assets to choose from. The vector of gross returns is given by $r_{t+1} = (r_{1,t+1}, ..., r_{n,t+1})$. If we suppose W_t is arbitrarily set to 1, then $W_{t+1} = \alpha_t^{'} r_{t+1}$, where α is an n by 1 vector of portfolio weights.

The investors problem is to choose α_t to maximize the expression

$$\begin{aligned}&\mathbb{E}_t[U(W_{t+1})] = \mathbb{E}_t[U(\alpha_t^{'} r_{t+1})]\\&= \int ... \int U(W_{t+1}) f(r_{t+1}) dr_{1,t+1} dr_{2,t+1} ... dr_{n,t+1}\end{aligned} \tag{2.2.4}$$

subject to the condition that $\sum_{i=1}^{n} \alpha_{i,t} = 1$, where $f(r_{t+1})$ is the joint probability distribution of r_{t+1}.

CARA and Normality reduce problem to mean-variance optimization

Let us further assume that the investor has CARA utility and that returns are conditionally normally distributed. The CARA utility assumption means the utility is given by

$U(W_{t+1}) = -e^{-\gamma W_{t+1}}$, where $\gamma \geq 0$ is the coefficient of absolute risk aversion. The distributional assumption $r_{t+1} \sim N(\mu_{t+1}, \Sigma_{t+1})$ implies that $W_{t+1} \sim N(\mu_{p,t+1}, \sigma^2_{p,t+1})$, where $\mu_{p,t+1} = \alpha_t^{'}\mu_{t+1}$ and $\sigma^2_{p,t+1} = \alpha_t^{'}\Sigma_{t+1}\alpha_t$

With the above two assumptions, expression (3.2.1) reduces to[11]

$$\mathbb{E}_t[U(W_{t+1})] = -\mathbb{E}_t[e^{-\gamma W_{t+1}}] = \gamma\mu_{p,t+1} - \frac{1}{2}\gamma^2\sigma^2_{p,t+1} \tag{2.2.5}$$

Equation (3.2.2) demonstrates that under the assumptions of CARA utility function and conditional normality of returns, the general portfolio allocation problem (3.2.1) reduces to the mean-variance optimization problem.[12]

If we further assume that our investor has a 2-asset portfolio made up of a nominally safe domestic bond and a foreign bond, and that she allocates a fraction α of her wealth to the domestic bond, then next period wealth expressed in local currency units is given by

$$W_{t+1} = \left[\alpha(1+i_t) + (1-\alpha)(1+i_t^*)\frac{S_{t+1}}{S_t.}\right] W_t \tag{2.2.6}$$

In this 2-asset example and CARA utility and conditionally normal returns the expressions for the conditional mean and variance of next period wealth are given by:

$$\begin{aligned} \mu_{p,t+1} &= \left[\alpha(1+i_t) + (1-\alpha)(1+i_t^*)\tfrac{\mathbb{E}_t S_{t+1}}{S_t}\right] W_t, \\ \sigma^2_{p,t+1} &= \tfrac{(1-\alpha)^2(1+i_t^*)^2 Var_t(S_{t+1})W_t^2}{S_t^2} \end{aligned} \tag{2.2.7}$$

[11]The second equality follows from the fact that $e^{-\gamma W_{t+1}} \sim LN(-\gamma\mu_{p,t+1}, \gamma^2\sigma^2_{p,t+1})$, so $\mathbb{E}_t[e^{-\gamma W_{t+1}}] = -\gamma\mu_{p,t+1} + \gamma^2\sigma^2_{p,t+1}$

[12]The quadratic utility function imply mean variance optimization for arbitrary return distribution. However, the quadratic utility implies increasing absolute risk aversion and satiation (Jondeau et al. (2010), page 352).

Plugging the expressions in equation (3.2.4) into objective function (3.2.2), taking the first order condition with respect to α and rearranging the first order condition yields the following equation which implicitly determines the optimal α:

$$(1+i_t) - (1+i_t^*)\frac{\mathbb{E}_t S_{t+1}}{S_t} = \frac{-\gamma W_t(1-\alpha)(1+i_t^*)^2 Var_t(S_{t+1})}{S_t^2}. \tag{2.2.8}$$

Equation (3.2.5) reduces to the UIP condition if we assume that all investors are risk-neutral ($\gamma = 0$):[13]

$$\frac{1+i_t}{1+i_t^*} = \frac{\mathbb{E}_t S_{t+1}}{S_t}. \tag{2.2.9}$$

The Fama regression in equation (2.2.2) tests a logarithmic version of equation (3.2.6). The key steps in deriving the testable restrictions in equation (3.2.6) are the joint assumptions of CARA utility and conditional normality of next period wealth, which reduce the investor's optimization to mean-variance. The above discussion illustrates that deriving the UIP equation tested through expression (2.2.2) depends on other assumptions *beyond* rational expectations and risk-neutrality. If the normality assumption is dropped, for example, then expression (3.2.6) will most likely include higher order moments. In fact, Jondeau et al. (2010) note that under CARA utility, if we drop the normality assumptions, then the investor would prefer positive skewness and low kurtosis, such that the investor's objective function in equation (3.2.2) will also include the third and fourth moments of the FX return distribution. Scott and Horvath (1980) show that a strictly risk-averse individual who always prefers more to less ($U^{(1)} > 0$) and likes positive skewness at all wealth levels will necessarily dislike high kurtosis.

Asset allocation under higher order moments

We showed in subsection (2.2.2) that the assumptions of CARA utility and normality of returns reduce the investor's problem to mean-variance optimization. However, if the distribution of portfolio returns is asymmetric, or the investor's utility function is of a higher order than the quadratic, or the mean and variance do not completely determine the

[13]UIP will also hold if $\alpha = 1$, regardless of investors' degree of risk Aversion.

distribution of asset returns, then higher order moments and their signs must be taken into account in the portfolio asset allocation problem. In this subsection we present a framework for incorporating higher order moments into the asset allocation problem.

The objective in (3.2.1) can be intractable and it is usual to focus on approximation of (3.2.1) based on higher order moments. Jondeau et al. (2010) consider a Taylor's series expansion of the utility function around expected utility up to the fourth order:

$$U(W_{t+1}) = U(\mathbb{E}_t W_{t+1}) + U^{(1)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1}) + \tfrac{1}{2!}U^{(2)}(W_{t+1})(W_{t+1} - \mathbb{E}W_{t+1})^2 + \tfrac{1}{3!}U^{(3)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1})^3 + \tfrac{1}{4!}U^{(4)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1})^4, \tag{2.2.10}$$

where $U^n(.)$ denotes the n^{th} derivative of the utility function with respect to next period wealth. Taking the conditional expectation of expression (2.2.10) yields

$$\mathbb{E}_t[U(W_{t+1})] \approx U(\mathbb{E}_t W_{t+1}) + U^{(1)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1}) + \tfrac{1}{2!}U^{(2)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1})^2 + \tfrac{1}{3!}U^{(3)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1})^3 + \tfrac{1}{4!}U^{(4)}(W_{t+1})(W_{t+1} - \mathbb{E}_t W_{t+1})^4. \tag{2.2.11}$$

Under the assumption that the investor's utility function is CARA, expression (2.2.11) reduces to

$$\mathbb{E}_t[U(W_{t+1})] \approx -e^{-\gamma\mu_p}\left[1 + \tfrac{\gamma^2}{2}\sigma_p^2 - \tfrac{\gamma^3}{6}s_p^3 + \tfrac{\gamma^4}{24}k_p^4\right]. \tag{2.2.12}$$

In equation (2.2.12), s_p^3 and k_p^4 are the skewness and kurtosis of portfolio return. It is clear from equation (2.2.12) that under CARA utility, investors prefer positive skewness and dislike high variance and high kurtosis. Optimal portfolio weights can then be obtained by maximizing expression (2.2.11) instead of the exact objective function shown in expression (3.2.1).

For CARA utility, the weight the investor puts on the higher order moments depends on the degree of risk aversion parameter γ. In more general settings, however, the weight on the n^{th} moment depends on the n^{th} derivative of the utility function, and the signs of sensitivities of utility function to changes in higher moments cannot be easily pinned down. If the moments are not orthogonal to each other, then the effect of utility of increasing one moment might not be straight forward. Scott and Horvath (1980) establish some general conditions for investor preference for skewness and kurtosis.

2.2.3 Why term structure of option-implied moments?

Rearranging the UIP relationship in equation (2.2.1) and iterating forward, we can show that the nominal exchange rate depends on current and expected future interest rate differentials as well as on expected future risk:

$$s_t = \underbrace{-\sum_{j=0}^{\infty} \mathbb{E}_t(i_{t+j} - i^*_{t+j})}_{\text{Expected future interest differentials}} - \underbrace{\sum_{j=0}^{\infty} \mathbb{E}_t \rho_{t+j}}_{\text{Expected Future FX risk}} \tag{2.2.13}$$

Expression (2.2.13) highlights the link between the exchange rate and macroeconomic fundamentals. There is a huge literature linking the term structure of interest rate rates(yield curve) to expected future dynamics of macroeconomic fundamentals such as monetary policy, inflation and output by observing that short term interest rates are monetary policy variables that depend on macroeconomic variables such as inflation and output while longer term yields are risk-adjusted averages of expected future short rates.[14] Chen and Tsang (2013) extend this strand of literature to the open economy context by noting that the term structure of interest rate differentials (relative yield curve) contain information about the expected future dynamics of differences in macroeconomic fundamentals. We note that the relative yield curve captures the same information about expected macroeconomic fundamentals as the term structure of option-implied *first* moments of future exchange rate movements. We extend the literature on yield curve-exchange rate linkage by investigating the ability of entire option-implied distributions to explain exchange rate dynamics.

Writing the exchange rate in the form in equation (2.2.13) also demonstrates the importance of capturing expectations and risk in the empirical modeling of exchange rate. Standard empirical approaches usually impose distributional assumptions that reduce the sum of expected future fundamentals to equal current fundamentals and also ignore risk. [15]

There is also a strand of literature that document the empirical success of empirical

[14]see Diebold et al. (2005) for a survey.

[15]see Engel and West (2005), Mark (1995).

exchange rate models that capture information in the term structure of forward premia.Clarida and Taylor (1997) and Clarida et al. (2003) show that even if the forward rate is a biased predictor of future spot rate (the forward premium puzzles),the term structure of forward premia still contains information useful for predicting subsequent exchange rate changes. This line of literature is linked to Chen and Tsang (2013) by observing that through the empirically valid covered interest parity (CIP) condition, the forward premium equals the interest rate differential at all maturities.

2.3 Information Content of Currency Options

2.3.1 Volatility Smile and Term Structure of Option Prices

Breeden and Litzenberger (1978) show that in complete markets, the call option pricing function (C) and the exercise price K are related as follows:

$$\frac{\partial^2 C}{\partial K^2} = e^{-r^d \tau} \pi_t^Q (S_{t+\tau}), \tag{2.3.1}$$

where r^d and r^f are the domestic and foreign risk-free interest rates and $\pi_t^Q(S_{t+\tau})$ is the risk-neutral probability density function (pdf) of future spot rates. Equation (2.3.1) implies that, in principle, we can estimate the whole pdf of time $S_{t+\tau}$ spot exchange rate from time t volatility smile. Once the distribution is available, it becomes possible to get empirical estimates of the standard deviation, skewness , kurtosis and even higher order moments of the market perceived probability density of $S_{t+\tau}$ given information available at time t.

In addition to the Breeden and Litzenberger (1978) result in equation (2.3.1), we note that although market participants can be treated as if they are risk-neutral for the purpose of option-pricing, option prices theoretically contain information about both investor beliefs and risk preferences, as shown from the following formula for the price of a European-style call option:

$$C(t, K, T) = \int_K^\infty \underbrace{M_{t,T}(S_T - K)}_{\text{Preferences}} \underbrace{\pi_t^P(S_T)}_{\text{Beliefs}} dS_T = e^{-r^d \tau} \int_K^\infty (S_T - K) \underbrace{\pi_t^Q(S_T)}_{\text{Both}} dS_T. \tag{2.3.2}$$

In equation (2.3.2), $M_{t,t+\tau}$ is the pricing kernel, which captures the investor's degree of risk aversion and $\pi_t^P(S_{t+\tau})$ is the physical probability density function of future spot exchange rates [16].

A forward contract can in fact be viewed as a European-style call option with a strike price of zero. To see this, we recall that, on one hand, the theoretical forward exchange rate is given by the formula:

$$F_{t,T} = e^{-r^d\tau}\int_0^\infty S_T\pi_t^Q(S_T)dS_T = e^{-r^d\tau}\mathbb{E}_t^Q(S_T). \tag{2.3.3}$$

On the other hand, evaluating equation (2.3.2) at K=0 yields:

$$C(t,0,T) = e^{-r^d\tau}\int_0^\infty S_T\pi_t^Q(S_T)dS_T = F_{t,T}. \tag{2.3.4}$$

The relationship between options and forwards in equation (2.3.4) suggests that the cross section of option prices should, at a minimum, contain as much information about investor beliefs and preferences as that contained in forward prices.

Moving on to the term structure of option prices, one way to motivate the theoretical information content of the term structure of option prices is to start from equation (2.2.13):

$$s_t = \underbrace{-\sum_{j=0}^{\infty}\mathbb{E}_t(i_{t+j} - i^*_{t+j})}_{\text{Expected future interest differentials}} - \underbrace{\sum_{j=0}^{\infty}\mathbb{E}_t\rho_{t+j}}_{\text{Expected Future FX risk}}. \tag{2.3.5}$$

Now, under the empirically valid CIP condition, interest rate differential is equal to the forward premium for all tenors j:[17]

$$i_{t+j} - i^*_{t+j} = f_t^{t+j} - s_t = -r^d\tau + \underbrace{E_t^Q\left[\ln\left(\frac{S_{t+j}}{S_t}\right)\right]}_{\text{First moment of } \pi_t^Q} + \underbrace{\omega_t}_{\text{Jensen's inequality term}}, \forall \text{ tenor } j. \tag{2.3.6}$$

[16] In the second expression, the pricing kernel is performing both the risk-adjustment and discounting functions, while in the third expression these functions are divided between π_t^Q and $e^{-r^d\tau}$.

[17] The second equality follows from dividing (2.3.3) by S_t and taking logarithms

Equation (2.3.6) thus says that, ignoring the Jensen's inequality term ω_t and the constant term $-r^d\tau$, the interest rate differential equals the first moment of the option-implied risk-neutral distribution of $\ln\left(\frac{S_{t+j}}{S_t}\right)$ for any given tenor j. The interest rates are monetary policy variables and therefore depend on macroeconomic fundamentals such as unemployment and inflation. When combined, equations (2.3.6) and (2.3.5) demonstrate that just like the yield curve, the term structure of the first moments of implied distributions also captures information about current and *expected* future macroeconomic fundamentals.

A second motivation for the information content of the term structure of option prices comes from the expectation hypothesis for implied volatility,that the term structure of option-implied volatility contain information about the market's perception about the future dynamics of short term implied volatility. If the expectations hypothesis holds in the FX market, then the implied volatility for long dated options should be consistent with the implied volatility of short dated options quoted today and in the future. [18]

2.3.2 Extracting Option-Implied Moments

We use the methodology of Bakshi et al. (2003b) (henceforth BKM) to extract model-free option-implied standard deviation, skewness and kurtosis from the volatility smile. Grad (2010) and Jurek (2009) also use the BKM methodology to extract FX options-implied higher order moments. [19] The BKM methodology rests on the results of Carr and Madan (2001), which show that if we have an arbitrary claim with a pay-off function H[S] with finite expectations, then H[S] can be replicated if we have a continuum of option prices. They also show that if H[S] is twice-differentiable, then it can be spanned algebraically by

---

[18]For example, if the current six month implied volatility is 10% and the current three month implied volatility is 5%, then, under the expectation hypothesis, then the three month implied volatility three months from now should be 13.2% because

$$0.5(0.1)^2 = 0.25(0.05)^2 + 0.25(0.132)^2.$$

[19]In this section we closely follow the exposition and notation in Grad (2010).

the following expression

$$H[S] = (H[\bar{S}] + (S - \bar{S}H_S[\bar{S}]) + \int_{\bar{S}}^{\infty} H_{SS}[K](S-K)^+ + \int_0^{\bar{S}} H_{SS}[K](K-S)^+ dK, \quad (2.3.7)$$

where $H_S = \frac{\partial H}{\partial S}$ and $H_{SS} = \frac{\partial^2 H}{\partial S^2}$. Assuming no arbitrage opportunities, the price of a claim with pay-off H[S] is given by the expression

$$p_t = (H[\bar{S}] - \bar{S}H_S[\bar{S}])e^{-r^d\tau} + H_S[\bar{S}]Se^{-r^d\tau} + \int_{\bar{S}}^{\infty} H_{SS}[K]C(t,\tau,K) + \int_0^{\bar{S}} H_{SS}[K]P(t,\tau,K)dK \quad (2.3.8)$$

where K is the strike price, $C(t,\tau,K)$ and $P(t,\tau,K)$ are, respectively, the prices of a European-style call and put options. $\bar{S}$ is some arbitrary constant, usually chosen to equal current spot price.

Equation (2.3.8) indicates that any pay-off function H[S] can be replicated by a position of $(H[\bar{S}] - \bar{S}H_S[\bar{S}])$ in the domestic risk-free bond, a position of $H[\bar{S}]$ in the stock, and combinations of out-of-the-money calls and puts, with weights $H_{SS}[K]$. Suppose we have contracts with the following pay-off functions:[20]

$$H[S] = \begin{array}{ll} [R_t(S_{t+\tau})]^2, & \text{Volatility Contract} \\ [R_t(S_{t+\tau})]^3, & \text{Cubic Contract} \\ [R_t(S_{t+\tau})]^4, & \text{Quartic Contract,} \end{array} \quad (2.3.9)$$

where $R_t(S_{t+\tau}) = ln(\frac{S_{t+\tau}}{S_t}\Big)$. BKM show that the variance, skewness and kurtosis of the distribution of $R_{t+\tau}$ can be calculated using the following formulas:

$$Stdev(t,\tau) = \sqrt{e^{r^d\tau}V(t,\tau) - \mu(t,\tau)^2} \quad (2.3.10a)$$

$$Skew(t,\tau) = \frac{e^{r^d\tau}W(t,\tau) - 3V(t,\tau)\mu(t,\tau)e^{r^d\tau} + 2\mu(t,\tau)^3}{[e^{r^d\tau}V(t,\tau) - \mu(t,\tau)^2]^{\frac{3}{2}}} \quad (2.3.10b)$$

$$Kurt(t,\tau) = \frac{e^{r^d\tau}X(t,\tau) - 4e^{r^d\tau}\mu(t,\tau)W(t,\tau) + 6e^{r^d\tau}\mu(t,\tau)^2V(t,\tau) - 3\mu(t,\tau)^4}{[e^{r^d\tau}V(t,\tau) - \mu(t,\tau)^2]^2} \quad , \quad (2.3.10c)$$

[20]One can use the framework to price contracts with higher order payoffs and therefore extract moments of order higher than 4. The point that we want to emphasize, that higher order moments matter, is demonstrated even if we only stop at 4^{th} order.

where the expressions for $V(t,\tau)$,$W(t,\tau)$ and $X(t,\tau)$ and $\mu(t,\tau)$ are given in appendix (.1). [21]

The BKM methodology described above requires a continuum of exercise prices. However, in the OTC FX options market implied volatilities are observed for only a discrete number of exercise prices. We therefore need a way to estimate the entire volatility smile from a few $(K-\sigma)$ pairs by interpolation and extrapolation. To this end, we use the Vanna Volga (VV) method described in Castagna and Mercurio (2007). The procedure allows us to build the entire volatility smile using only three points. Castagna and Mercurio (2007) note that if we have three options with implied volatility σ_1,σ_2, σ_3 and corresponding exercise prices K_1,K_2 and K_3 such that $K_1 < K_2 < K_3$, then the implied volatility of an option with arbitrary exercise price K can be accurately approximated by the following expression:

$$\sigma(K) = \sigma_2 + \frac{-\sigma_2 + \sqrt{\sigma_2^2 + d_1(K)d_2(K)(2\sigma_2 D_1(K) + D_2(K))}}{d_1(K)d_2(K)}, \tag{2.3.11}$$

where

$$D_1(K) = \frac{ln\left[\frac{K_2}{K}\right] ln\left[\frac{K_3}{K}\right]}{ln\left[\frac{K_2}{K_1}\right] ln\left[\frac{K_3}{K_1}\right]}\sigma_1 + \frac{ln\left[\frac{K}{K_1}\right] ln\left[\frac{K_3}{K}\right]}{ln\left[\frac{K_2}{K_1}\right] ln\left[\frac{K_3}{K_2}\right]}\sigma_2 + \frac{ln\left[\frac{K}{K_1}\right] ln\left[\frac{K}{K_2}\right]}{ln\left[\frac{K_3}{K_1}\right] ln\left[\frac{K_3}{K_2}\right]}\sigma_3 - \sigma_2,$$

$$D_2(K) = \frac{ln\left[\frac{K_2}{K}\right] ln\left[\frac{K_3}{K}\right]}{ln\left[\frac{K_2}{K_1}\right] ln\left[\frac{K_3}{K_1}\right]} d_1(K_1)d_2(K_1)(\sigma_1 - \sigma_2)^2 + \frac{ln[\frac{K}{K_1}]ln[\frac{K}{K_2}]}{ln[\frac{K_3}{K_1}]ln[\frac{K_3}{K_2}]} d_1(K_3)d_2(K_3)(\sigma_3 - \sigma_2)^2$$

and

$$d_1(x) = \frac{log[\frac{S_t}{x}] + (r^d - r^f + \frac{1}{2}\sigma_2^2)\tau}{\sigma_2\sqrt{\tau}}, d_2(x) = d_1(x) - \sigma_2\sqrt{\tau}, x \in K, K_1, K_2, K_3.$$

Expression (2.3.11) allows us to find the implied volatility of an option with an arbitrary strike price. We use $K_1 = K_{25\delta p}$, $K_2 = K_{ATM}$ and $K_3 = K_{25\delta c}$. The VV methodology is preferable because it is parsimonious as it uses only three option combinations to build

[21] Derivations of equations in (2.3.10) and expressions for $\mu(t,\tau), V(t,\tau), W(t,\tau)$ and $X(t,\tau)$ can be found in Bakshi et al. (2003b) and Grad (2010).

an entire volatility smile. [22] Furthermore,the VV method also has a solid it is based on a replication argument in which an investor constructs a portfolio that, in addition to hedging against movements in the price of the underlying asset ($\delta = \frac{\partial C}{\partial S}$), also hedges against movements in volatility of the underlying asset ($Vega = \frac{\partial C}{\partial \sigma}$).

2.3.3 Data Description

In the o-t-c market, the exchange rate is quoted as the domestic price of foreign currency, so a fall in the exchange rate represents an appreciation of domestic currency.

Compared to exchange-traded options, there are several advantages that come with using o-t-c data in our empirical analysis. First, most of the FX options trading is concentrated in the o-t-c market. This means o-t-c currency options prices are more competitive and therefore more likely to be representative of aggregate market beliefs compared to prices in the less liquid exchange market. [23] A second advantage of using o-t-c option price data is that fresh options for standard tenors are quoted each day, making it possible to obtain a time series of FX option prices with constant maturities. Lastly,unlike American-style options traded in the exchange market, European-style options that are traded in the o-t-c market do not need to be adjusted for the possibility of early exercise.

We next explain some important OTC currency market quoting conventions. First, option prices are given in terms of implied volatility instead of currency units while “moneyness” is measured in terms of the delta of an option. The delta of an option is a measure of the responsiveness of the option’s price with respect to a change in the price of the underlying asset. If the prices of call and put options are given by C_t and P_t, then option price and

[22]This is the minimum number that can be used if one wants to capture the three most prominent movements in the volatility smile: change in level, change in slope, and change in curvature.The ATM straddle, VWB and the Risk Reversal capture these movements. See discussions in Castagna (2010) and Malz (1998)

[23]Table (3.1C), obtained from the 2010 BIS Triennial Survey, shows that although the o-t-c options market is small relative to the overall FX market, it is very liquid and rapidly growing when we look at it in absolute terms.

implied volatility are linked using the Black-Scholes formula applied to FX:

$$
\begin{aligned}
C_t &= e^{-r^d\tau}\left[F_t^{t+\tau}\Phi(d_1) - K\Phi(d_2)\right] \\
P_t &= e^{-r^d\tau}\left[K\Phi(-d_2) - F_t^{t+\tau}\Phi(-d_1)\right]
\end{aligned}
$$

where

$$d_1 = \frac{log[\frac{S_t}{K}] + (r^d - r^f + \frac{1}{2}\sigma_2^2)\tau}{\sigma_2\sqrt{\tau}}, d_2 = d_1 - \sigma_2\sqrt{\tau}.$$

The expressions for call and put deltas are given by the expressions:

$$\delta_c = e^{-r^f}\Phi(d_1) \tag{2.3.12a}$$

$$\delta_p = e^{-r^f}\Phi(-d_1), \tag{2.3.12b}$$

where $\Phi(.)$ is the standard normal cumulative density function (cdf). The absolute values of δ_c and δ_p are therefore between 0 and 1, while put-call parity implies that $\delta_p = \delta_c - 1$. [24]

Lastly, in the FX o-t-c option market, prices are quoted in combinations rather than simple call and put options. The most common option combinations are at-the-money (ATM)[25] straddle, risk reversals (RR), and Vega-weighted butterflies (VWB). An ATM straddle is the sum of a base currency call and a base currency put, both struck at the current forward rate. An RR is set up when one buys a base currency call and sells a base currency put with a symmetric delta. Finally, a VWB is built by buying a symmetric delta strangle and selling an ATM straddle. [26] The 25δ combination is the most traded options VWB.

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[24] The market convention is to quote a delta of magnitude x as a $100 * x$ delta. For example, a put option with a delta of -0.25 is referred to as a 25δ put.

[25] "ATM here means the delta of the option combination is zero. That is, the option combination is "delta-neutral"

[26] In a strangle, you buy an out of the money call and an equally out of the money put

[27] The definitions of the three option combinations are as follows:[28]

$$\sigma_{ATM,\tau} = \sigma_{0\delta c,\tau} = \sigma_{50\delta c} + \sigma_{50\delta p} \tag{2.3.13a}$$

$$\sigma_{25\delta RR,\tau} = \sigma_{25\delta c,\tau} - \sigma_{25\delta p,\tau} \tag{2.3.13b}$$

$$\sigma_{25\delta vwb,\tau} = \underbrace{\frac{\sigma_{25\delta c,\tau} + \sigma_{25\delta p,\tau}}{2}}_{\text{Strangle}} - \sigma_{ATM,\tau} \tag{2.3.13c}$$

Equations (2.3.13) can be rearranged to get the implied volatility for 0δ call, 25δ call and 25δ put. Expressions for backing out implied volatility of these"plain-vanilla" options from the prices of traded option combinations are given below:

$$\sigma_{0\delta c,\tau} = \sigma_{ATM} = \sigma_{50\delta c,\tau} + \sigma_{50\delta p,\tau} \tag{2.3.14a}$$

$$\sigma_{25\delta c,\tau} = \sigma_{ATM} + \sigma_{25\delta vwb,\tau} + \frac{1}{2}\sigma_{25\delta RR,\tau} \tag{2.3.14b}$$

$$\sigma_{25\delta p,\tau} = \sigma_{ATM} + \sigma_{25\delta vwb,\tau} - \frac{1}{2}\sigma_{25\delta RR,\tau}. \tag{2.3.14c}$$

Finally, $K_{25\delta p}$, K_{ATM}, $K_{25\delta c}$, the exercise prices corresponding to $\sigma_{ATM,\tau}$, $\sigma_{25\delta c,\tau}$ and $\sigma_{25\delta p,\tau}$ can be backed out by using the expression for option deltas given in equation (2.3.12). For example, to get K_{ATM} we use the fact that the ATM straddle has a delta of zero:

$$e^{-r^f\tau}\left[\Phi\left(\frac{ln[\frac{S_t}{K_{ATM}}] + (r^d - r^f + \frac{1}{2}\sigma^2_{ATM})\tau}{\sigma_{ATM}\sqrt{\tau}}\right) - \Phi\left(-\frac{ln[\frac{S_t}{K_{ATM}}] + (r^d - r^f + \frac{1}{2}\sigma^2_{ATM})\tau}{\sigma_{ATM}\sqrt{\tau}}\right)\right] = 0. \tag{2.3.15}$$

[27] The ATM straddle, risk reversal and strangle are usually interpreted as short cut indicators of volatility, skewness and kurtosis of the perceived conditional distribution of exchange rate movements. The profit diagrams in figure (2.1) demonstrate why:

(i) the straddle becomes profitable if there is a movement in the underlying asset's price

(ii) the risk-reversal makes profit if there is a movement in a particular direction

(iii) the strangle becomes profitable if there is a *big* movement in any direction in the underlying asset's price.

[28]Table (3.1B) contains sample option price quotes for standard combinations and standard maturities.

Since $\Phi(.)$ is a monotone function, we can solve equation (2.3.15) for K_{ATM} to get:

$$K_{ATM} = S_t e^{(r^d - r^f + \frac{1}{2}\sigma^2_{ATM})\tau} = F_t^{t+\tau} e^{\frac{1}{2}\sigma^2_{ATM}}. \tag{2.3.16}$$

Using similar arguments, one can show that the expressions for $K_{25\delta c}$ and $K_{25\delta p}$

$$K_{25\delta c} = S_t e^{[-\Phi^{-1}(\frac{1}{4}e^{r^d\tau})\sigma_{25\delta c,\tau}\sqrt{\tau} + (r^d - r^f + \frac{1}{2}\sigma^2_{25\delta c})\tau]} \tag{2.3.17a}$$

$$K_{25\delta p} = S_t e^{[\Phi^{-1}(\frac{1}{4}e^{r^d\tau})\sigma_{25\delta p,\tau}\sqrt{\tau} + (r^d - r^f + \frac{1}{2}\sigma^2_{25\delta p})\tau]}, \tag{2.3.17b}$$

with $K_{25\delta p} < K_{ATM} < K_{25\delta c}$ (Castagna and Mercurio (2007)).

Our options data consists of over the counter (o-t-c) option prices for the six currency pairs listed in table (3.1A) and covering the period 1 January 2007 to April 19 2011.

The spot rates, forward rates and risk-free interest rates are obtained from Datastream.

2.4 Empirical Strategy and Main Results

2.4.1 Empirical properties of extracted option-implied moments

Time series plots of the extracted risk neutral moments of $log\frac{S_T}{S_t}$ are shown in figure (2.2). The extracted moments are very persistent, with AR(1) coefficients as high as 0.99. Zivot and Andrews (1992) unit root tests, however, suggest that almost all the implied moments are stationary,with structural breaks in the means on dates around late 2008 and early 2009. There are also some outliers in some of the skewness and kurtosis series, especially for 9m and 12m tenor.[29]

INSERT FIGURE (2.2) HERE

[29]Summary statistics of the extracted moments can be found in the online appendix to this paper.

2.4.2 Can the term structure of implied moments predict currency returns?

For each currency pair i, we start by estimating the standard UIP regression

$$s^i_{t+\tau} - s^i_t = \alpha + \beta(f^{t+\tau i}_t - s^i_t) + \epsilon^i_{t+\tau}. \tag{2.4.1}$$

We focus on model fit and joint significance rather than testing whether the β coefficient is equal to 1. Fitted vs Actual plots of estimated regression (2.4.1) (with breaks) are shown in figures 2.4(a)-2.4(e), while condensed results can be found in column **A** of table (2.4). For all currency pairs, the forward premia coefficients are statistically significant at the 1% level, and adjusted R^2 of at least 10% for each currency pair.

We then consider the predictive ability of τ-period option-implied higher moments by estimating the following augmented UIP regression:

$$s^i_{t+\tau} - s^i_t = \alpha + \beta_1(f^{i,t+\tau}_t - s_t) + \beta_2 stdev^{i,t+\tau}_t + \beta_3 skew^{i,t+\tau}_t + \beta_4 kurt^{i,t+\tau}_t + \epsilon_{i,t+\tau} \tag{2.4.2}$$

Equation (2.4.2) therefore augments the standard UIP equation (2.4.1) by studying the predictive ability of the $1^{st} - 4^{th}$ moments of the distribution of $log\left(\frac{S_{t+\tau}}{S_t}\right)$. The condensed regressions results are shown in column **B** table (2.4) . The adjusted R^2s for the matched-frequency augmented UIP regressions are consistently higher than those from the standard UIP specification in column **A**, ranging from 26% to 67%. Coefficients on the higher order moments are always jointly significant at the 1% level.

We next estimate a term structure modification of the standard UIP equation (2.4.1) that uses information contained in the term structure of forward premia to predict exchange rate movements:

$$s^i_{t+\tau} - s^i_t = \gamma_{0,\tau} + \sum_{j=1}^{3} \gamma_{1,j} PC_j meanTerm + \epsilon^i_{t+\tau}. \tag{2.4.3}$$

Condensed results from regression specification (2.4.3) are presented in column **C** of table (2.4). Comparing columns **A** and **C** in table (2.4), we see that adding the whole term structure of forward premia significantly improves the UIP regression fit. For example, the adjusted R^2 jumps from 27% to 57% for AUDUSD, 15% to 40% for EURUSD and from 15% to 54% for USDCAD.

Lastly, we regress exchange rate movements on the term structure of $1^{st} - 4^{th}$ moments:

$$\begin{aligned} s^i_{t+3M} - s^i_t = \gamma_{0,\tau} + \sum_{j=1}^{3} \gamma_{1,j} PC_j meanTerm^i + \sum_{j=1}^{3} \gamma_{2,j} PC_j stdevTerm^i + \\ \sum_{j=1}^{3} \gamma_{3,j} PC_j skewTerm^i + \sum_{j=1}^{3} \gamma_{4,j} PC_j kurtTerm^i + \epsilon^i_{t+3M}. \end{aligned} \tag{2.4.4}$$

Plots of actual versus fitted values from regressions (2.4.4) and (2.4.1) are shown in figures (2.4). These plots show that considered with the standard UIP regression, accounting for higher order moment risks and expectations substantially improves that model fit. The condensed regression results for the higher moment term structure specification, shown in column **D** of table (2.4) show that compared to the UIP specification in column **A**, accounting of for higher moments and expectations,for example, increases adjusted R^2 from 27% to 67% for AUDUSD, 15% TO 53% for EURUSD and from 10% to 57% for USDJPY.

INSERT TABLE (2.4) AND FIGURE (2.4) HERE

2.4.3 Can option-implied moments forecast FX excess returns?

Matched Frequency Analysis: Predictive ability of the volatility smile

For each currency pair i, we start by investigating the predictive ability of $\tau - period$ option-implied measures of standard deviation, skewness and kurtosis for subsequent excess currency returns[30]:

$$f^{i,t+\tau}_t - \mathbb{E}_t(s^i_{t+\tau}) = \gamma_{0,\tau} + \gamma_{1,\tau} stdev^{i,t+\tau}_t + \gamma_{2,\tau} skew^{i,t+\tau}_t + \gamma_{3,\tau} kurt^{i,t+\tau}_t + u_{i,t+\tau}. \tag{2.4.5}$$

[30]Excess returns are a component of the expected exchange rate movements since $\mathbb{E}_t(s^i_{t+\tau}) - s^i_t$ can be decomposed into excess returns $-(f^{i,t+\tau}_t - \mathbb{E}_t(s^i_{t+\tau}))$ and the interest differential, which equals $f_t - s_t$ under CIP.

Under rational expressions, $f_t^{i,t+\tau} - \mathbb{E}_t(s_{t+\tau}^i)$ is also equal to the risk premium. Gereben (2002) and Malz (1997) also estimate regression specification (2.4.5) and interpret the results in light of the time-varying risk premia explanation of the UIP puzzle. Gereben (2002) argues that if the forward bias is due to time-varying risk premia, then variables that capture the nature of FX risk should be able to explain the dynamics of the forward bias. The option-implied moments on the RHS in regression equation 2.4.5), which capture perceived FX volatility, tail and crash risk should therefore be able to explain the forward bias. Malz (1997) also argues that statistical significance of the coefficient on $skew_t^{t+\tau}$ can be interpreted as providing support for the peso problem explanation of the UIP puzzle.

Going back to expression 2.4.5), we note that $\mathbb{E}_t(s_{t+\tau})$ is not observable. If we assume that market participants have rational expectations, then $\mathbb{E}_t(s_{t+\tau})$ and $s_{t+\tau}$ will only differ by a forecast error ν_{t+1} that is uncorrelated with all variables that use information at time t, such that

$$s_{t+\tau} = \mathbb{E}_t(s_{t+\tau}) + \nu_{t+1}. \tag{2.4.6}$$

Plugging equation (2.4.6) into equation (2.4.5) and rearranging gives us the following estimable regression equation:

$$xr_{t+\tau} = \gamma_{0,\tau} + \gamma_{1,\tau} stdev_t^{t+\tau} + \gamma_{2,\tau} skew_t^{t+\tau} + \gamma_{3,\tau} kurt_t^{t+\tau} + \epsilon_{t+\tau} \tag{2.4.7}$$

where the error term $\epsilon_{t+\tau} = u_{t+\tau} + \nu_{t+\tau}$ and $xr_{t+\tau}$ is ex-post excess returns defined in expression (2.2.3).

To provide intuition regarding expected coefficient signs in the regression equation (2.4.7), we take the point view of a domestic investor who invests in domestic bonds using money borrowed from abroad. As shown in equation (2.2.3), such an investor benefits from higher domestic interest rates as well as appreciation of domestic currency. Let's also assume that the home currency is riskier, such that our investor would demand higher excess returns for higher *stdev* and *kurtosis* in the exchange rate. If investors are averse to high variance and kurtosis, they would require higher excess returns for holding bonds denominated in units of the riskier domestic and we would expect the coefficients on *stdev* and *kurtosis* to be both positive. We expect the *skew* coefficient to be positive for investor's with preference for positive skewness. Such an investor will require higher compensation for an increase in *skew*, which represents a higher perceived likelihood of domestic currency depreciation.

Given the discussion in subsection (2.2.2), however, we note that pinning down the coefficient signs a priori is impossible without making further assumptions about the investor's utility function or orthogonality of the moments. In our regression analysis, we therefore focus mainly on joint significance of the explanatory variables and model fit rather than on significance and signs of individual coefficients.

Sub-sample analyses suggest the presence of structural breaks in the matched-frequency regression relationships for the majority of currency pairs and tenors. We use the Bai and Perron (2003) structural break test to identify the date for the most prominent break [31] and estimate a modification of regression equation (2.4.7) that includes interactions with structural break indicator variable:

$$\begin{aligned} xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{2,\tau} skew^{i,t+\tau}_t + D1^{i,\tau} * \\ \gamma_{3,\tau} kurt^{i,t+\tau}_t + \gamma_{4,\tau} stdev^{i,t+\tau}_t + \gamma_{5,\tau} skew^{i,t+\tau}_t + \gamma_{6,\tau} kurt^{i,t+\tau}_t + \epsilon^i_{t+\tau}. \end{aligned} \tag{2.4.8}$$

where $D1^{i,\tau}$ is an indicator variable that is zero before the break date and equal to one otherwise.

The matched-frequency results, shown in tables 2.9(a)-2.9(f), demonstrate a consistent ability of options-based measures of FX standard deviation, skewness and kurtosis-proxying to explain excess currency returns. The coefficients on the six non-intercept terms are always jointly significant at the 1% level. The adjusted R^2s for example, range from 13% (USDJPY) to 28% for 1 month tenor and from 20%(USDJPY) to 42% (EURJPY) for the 3M tenor.

We next go beyond OLS regression, which models the conditional mean of the the dependent variable given the explanatory variables, by using quantile regression analysis (QR) to investigate the predictive ability of options-based FX risk measures for the entire distribution of ex-post excess currency returns. By modeling the entire distribution of the

[31] We only focus on the major breaks, and therefore do not choose the number of breaks according to information criteria such as AIC.

dependent variable, QR allows us to get a more complete picture of the predictive ability of the option-implied moments. QR also has a further advantage over OLS in that it is robust to outliers in the dependent variable and does not impose restrictive distributional assumptions on the error terms.

We estimate the following linear quantile regression model, modified to include one break:

$$Q_i^{xr}(\theta|.) = \gamma_{0,\tau} + \gamma_{1,\tau} STDEV_t^{i,t+\tau} + \gamma_{2,\tau} SKEW_t^{i,t+\tau} + \gamma_{3,\tau} KURT_t^{i,t+\tau} + \epsilon_{i,t+\tau}, \quad (2.4.9)$$

where $Q_i^{xr}(\theta|.)$ is the θ^{th} quantile of excess returns given information available at time t.[32]

Matched-frequency quantile regression results for 3M tenor are shown in tables (2.8a)-(2.8f). We find that the coefficients on non-intercept terms are always jointly significant across quantiles for all currency pairs. Adjusted R^2s range from 13% to 44% for AUDUSD, and 12% to 30% for USDJPY for example. Another consistent pattern across currency pairs and tenors is that option-implied moments have more predictive ability for lower and upper quantiles of excess returns than the middle quantiles.

INSERT TABLES (2.8a)- (2.8f)HERE

Can the term structure of implied moments predict excess currency returns?

We first extend regression equation (2.4.7) by regressing 3M bilateral excess returns on 1M, 3M and 12M option-implied moments. That is, for each currency pair i, we estimate the following OLS regression:

$$xr_{t+3M}^i = \gamma_{0,3M} + \sum_j \gamma_{1,\tau_j} stdev_t^{t+\tau_j,i} + \sum_j \gamma_{2,\tau_j} skew_t^{t+\tau_j,i} + \sum_j \gamma_{3,\tau_j} kurt_t^{t+\tau_j,i} + \epsilon_{t+3M}^i, \quad (2.4.10)$$

where $j \in \{1M, 3M, 12M\}$. Similar to the matched-frequency analysis in subsection (2.4.3), our final term structure regression model is a modification of (2.4.10) in which we include interactions with a structural break indicator variable $D1$. Regression results from specification

[32]We estimate the quantile regression model using the same break dates obtained in the OLS analysis

(2.4.10) (with break) are shown in column **B** of table (2.3). Compared to the matched frequency results presented in column **A**, we see a huge increase in the adjusted R^2s. For example, adjusted R^2 increases from 33% to 62% for AUDUSD, 34% to 49% for EURUSD, and from 20% to 36% for USDJPY.

In column **C** of table (2.3) , we present condensed results of regressions that incorporate information from all tenors (not just 1M,3M and 12M) by using principal components extracted from all tenors.

Column **C** therefore contains results from the following regression:

$$xr^i_{t+3M} = \gamma_{0,\tau} + \sum_{j=1}^{3} \gamma_{2,j} PC_j stdevTerm^i + \sum_{j=1}^{3} \gamma_{3,j} PC_j skewTerm^i + \sum_{j=1}^{3} \gamma_{4,j} PC_j kurtTerm^i + \epsilon^i_{t+3M}. \tag{2.4.11}$$

In equation (2.4.11), $PC_j xxxxTerm^i$ refers to the j^{th} principal component extract from the currency i term structure of option-implied moment $xxxx$. Results from estimation regression equation (2.4.11) are in column **C** of table (2.3).

Lastly, we extend the specification in (2.4.11) by adding information from the term structure of first moments as additional regressors:

$$xr^i_{t+3M} = \gamma_{0,\tau} + \sum_{j=1}^{3} \gamma_{1,j} PC_j meanTerm^i + \sum_{j=1}^{3} \gamma_{2,j} PC_j stdevTerm^i + \sum_{j=1}^{3} \gamma_{3,j} PC_j skewTerm^i + \sum_{j=1}^{3} \gamma_{4,j} PC_j kurtTerm^i + \epsilon^i_{t+3M}. \tag{2.4.12}$$

The term structure of first moments captures expectations of the dynamics of future macroeconomic fundamentals. We use the term structure of interest rate differentials to extract the principal components of the term structure of first moments of $\log\left(\frac{S_{t+\tau}}{S_t}\right)$.[33]

[33] As noted earlier,the forward premium, which is the theoretical mean of the risk-neutral probability density of $\log\left(\frac{S_{t+\tau}}{S_t}\right)$ is equal to the interest differential $i^\tau - i^{*,\tau}$.

Using yield curve data to extract the term structure of first moments has the advantage of allowing us to also use interest rate differentials for tenors not covered by our option price data. As with our previous regressions, we estimate a version of regression model (2.4.12) that includes interactions with a structural break indicator variable.

The condensed results from estimating equation (2.4.12) with breaks are presented in column (**D**) of table (2.3). Actual vs fitted plots from this regression are shown in figures (2.3(a)-2.3(e)).

INSERT FIGURE (2.3) AND TABLE (2.3) HERE

Compared to the matched frequency regressions column **A** of table (2.3), inclusinf the term structure of $1^{st}-4^{th}$ moments increases the adjusted R^2 from 33% to 66% for AUDUSD, 34% TO 51% for EURUSD, 48% to 83% for GBPUSD, 48% to 62% for USDCAD and from 20% to 57% for USDJPY. These dramatic improvements in the model fit further highlight the importance of properly accounting for expectations and higher moment risks.

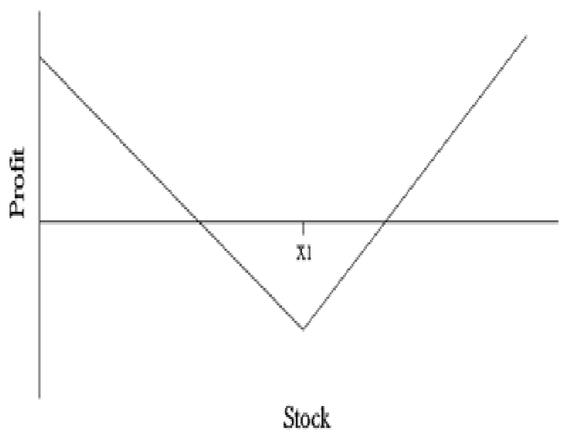
2.5 Conclusion

This paper has documented a robust ability of options-implied measures of FX higher moment risks to explain subsequent excess currency returns and FX returns. We also find that the term structure of such risks, capturing forward-looking property of the exchange rate, add further explanatory power. Our findings suggest that expectation and risk should be given more careful consideration in the structural modeling and empirical testing of exchange rate models.

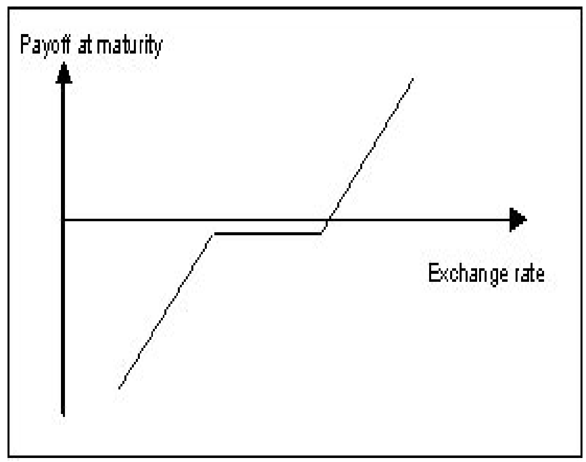
This paper can be extended in several directions that are useful to academics, monetary policy officials and investment professionals. First, how useful is the option-based information for out-of-sample forecasting of exchange rate. The ability to accurately forecast exchange rates movements for many purposes, including determining the future value of foreign denominated debt payments and for hedging for investment managers exploiting international investment opportunities. Second, an empirical analysis of the macroeconomic variables and events that drive the option-implied moments would further shed light on the link between exchange rates and fundamentals.

Figure 2.1: Profit diagrams for options strategies

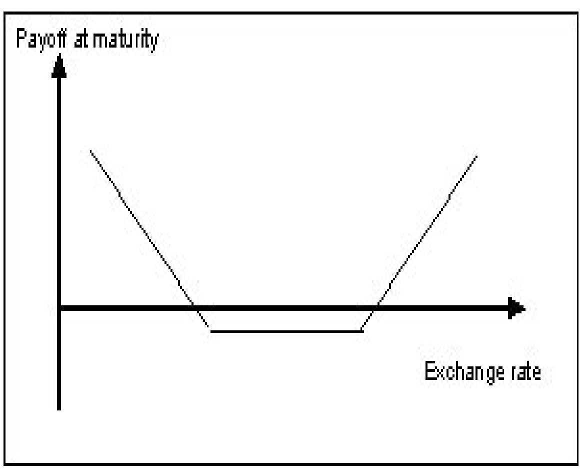
(a) Profit Function of a Straddle



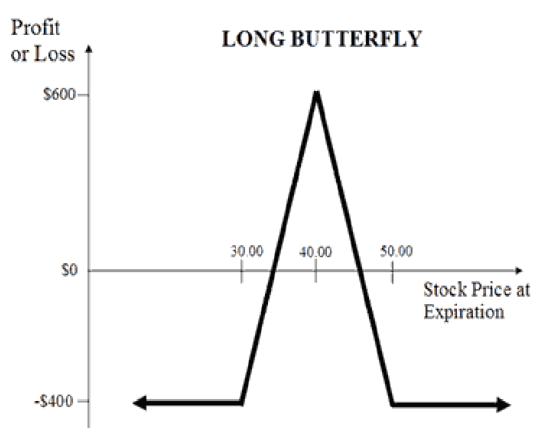
(b) Profit Function of a Risk Reversal



(c) Profit Function of a Strangle



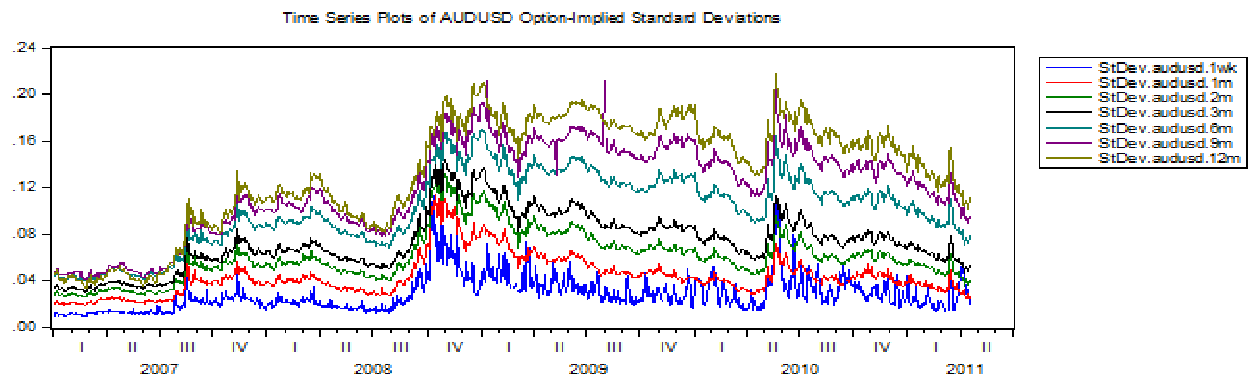
(d) Profit Function of a Butterfly



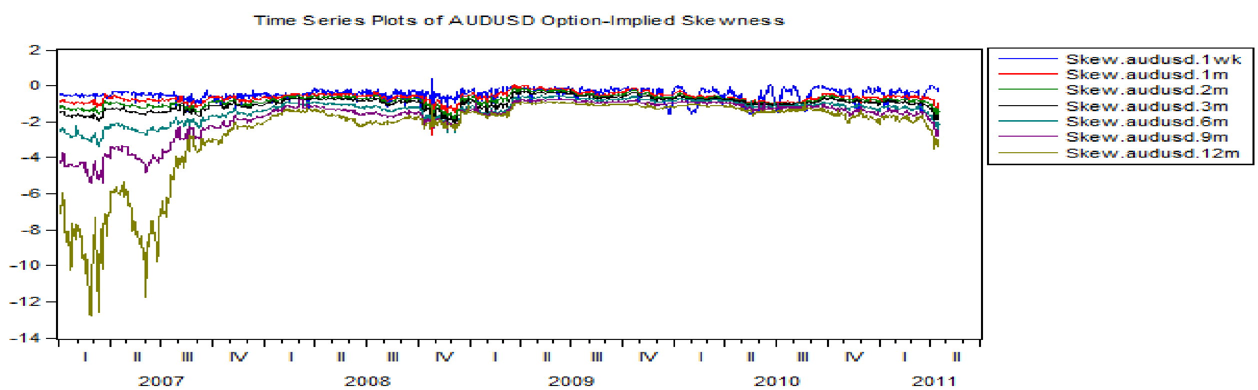
Note: Straddle,Risk Reversal,Strangle and Butterfly are as defined in subsection (3.3.1)

Figure 2.2: Time Series Evolution Of Option Implied Moments

(a) AUDUSD STDEV



(b) AUDUSD SKEWNESS



(c) AUDUSD KURTOSIS

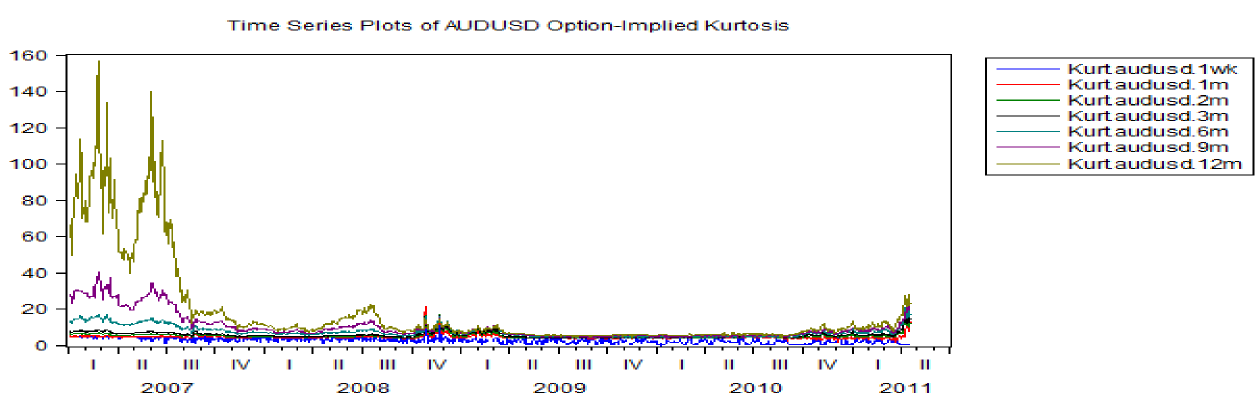
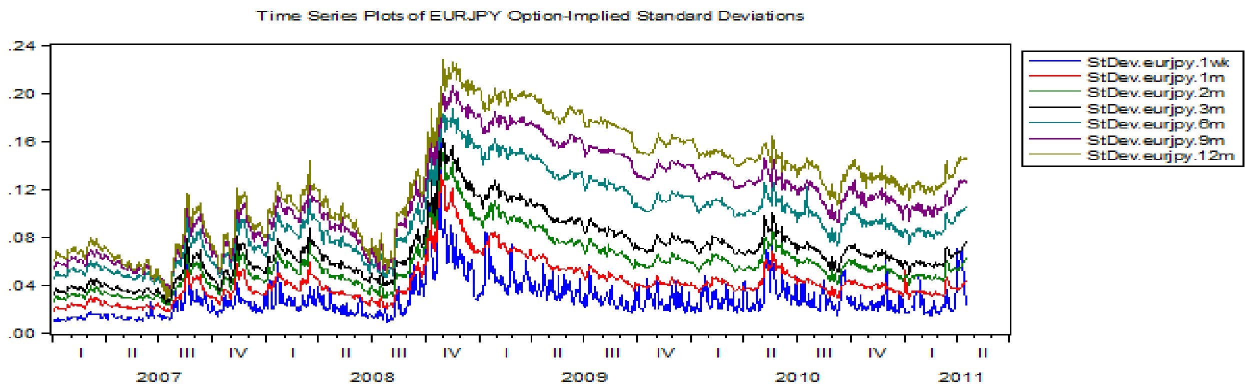
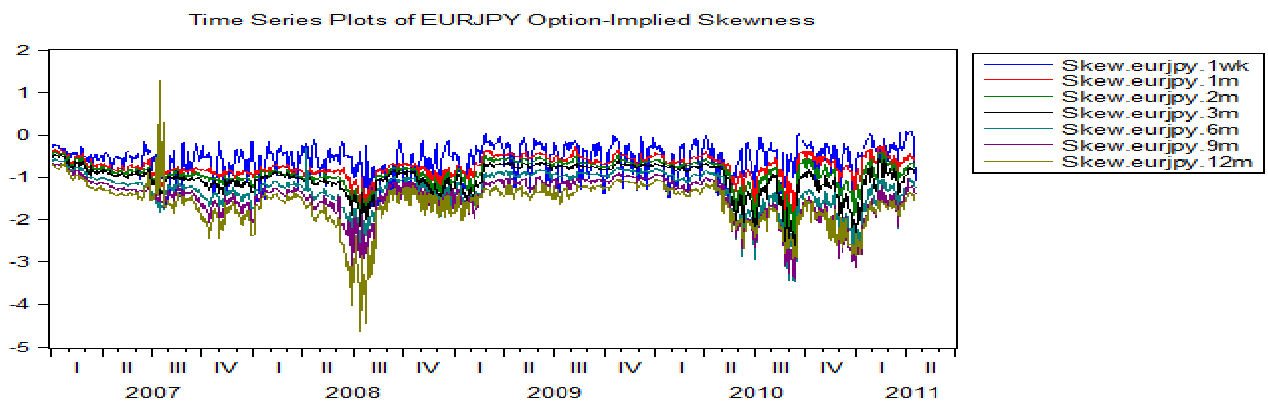


Figure 2.2: Time Series Evolution Of Option Implied Moments

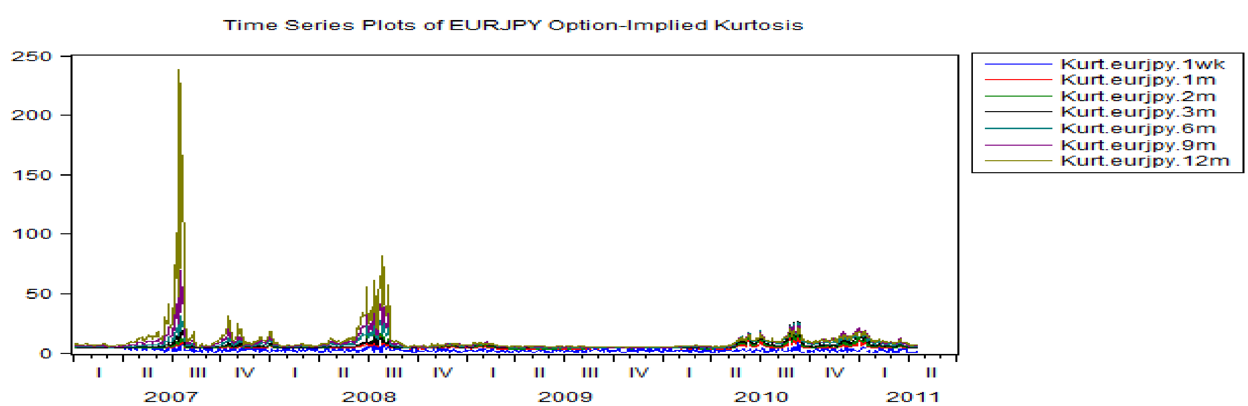
(d) EURJPY STDEV



(e) EURJPY SKEWNESS



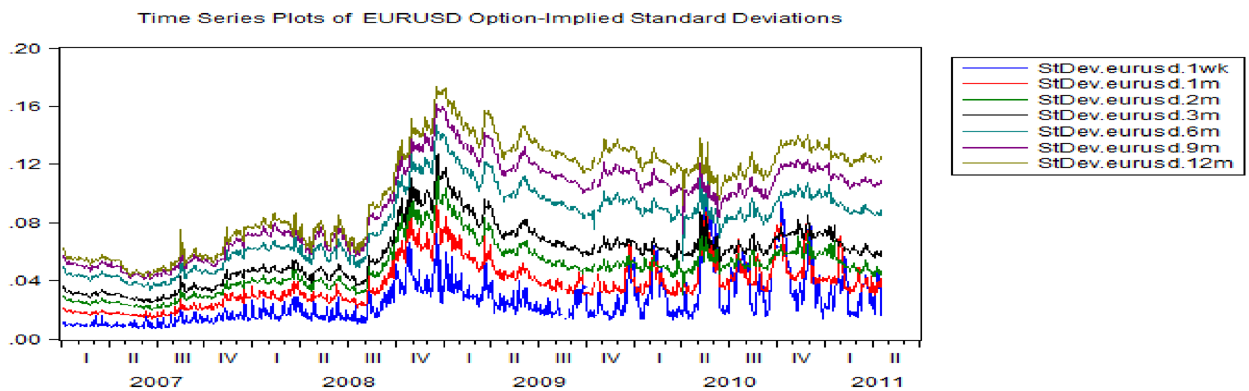
(f) EURJPY KURTOSIS



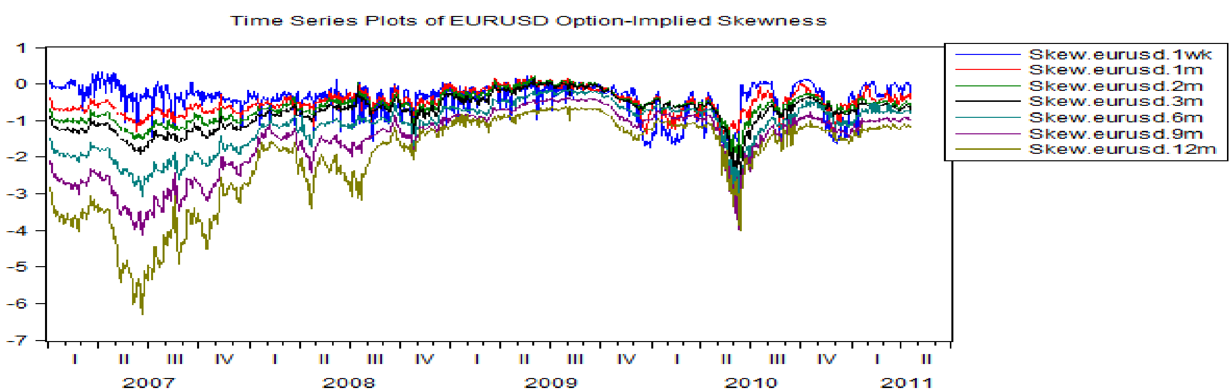
Note: Moments extracted using the methodology developed in Bakshi et al. (2003b).

Figure 2.2: Time Series Evolution Of Option Implied Moments

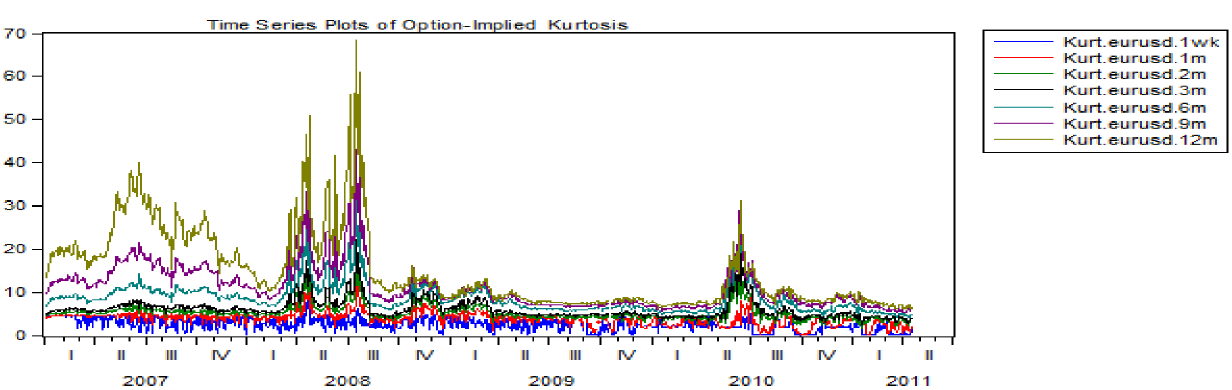
(g) EURUSD STDEV



(h) EURUSD SKEWNESS



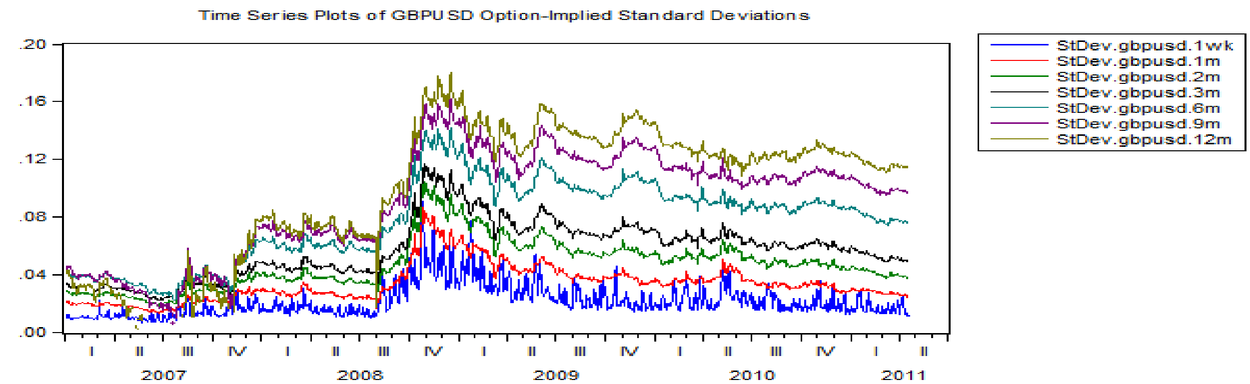
(i) EURUSD KURTOSIS



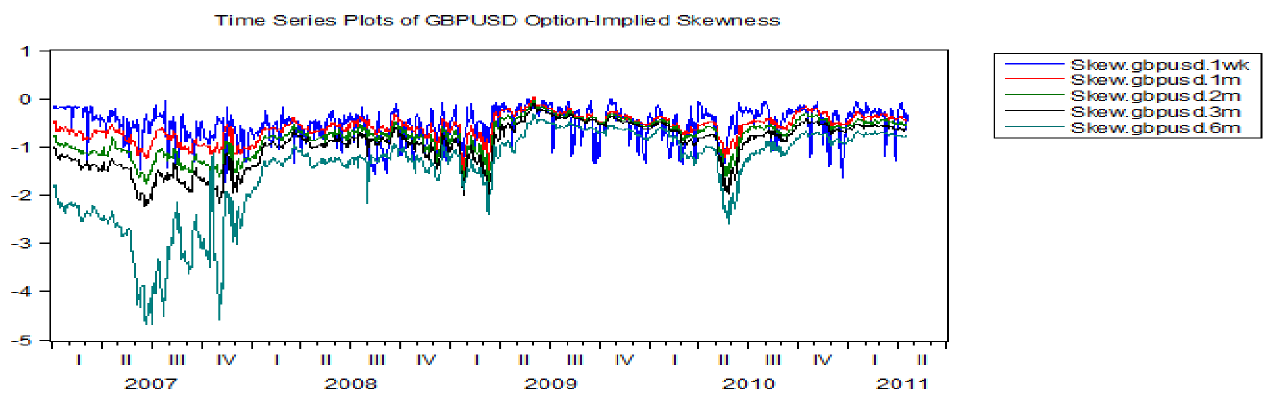
Note: Moments extracted using the methodology developed in Bakshi et al. (2003b).

Figure 2.2: Time Series Evolution Of Option Implied Moments

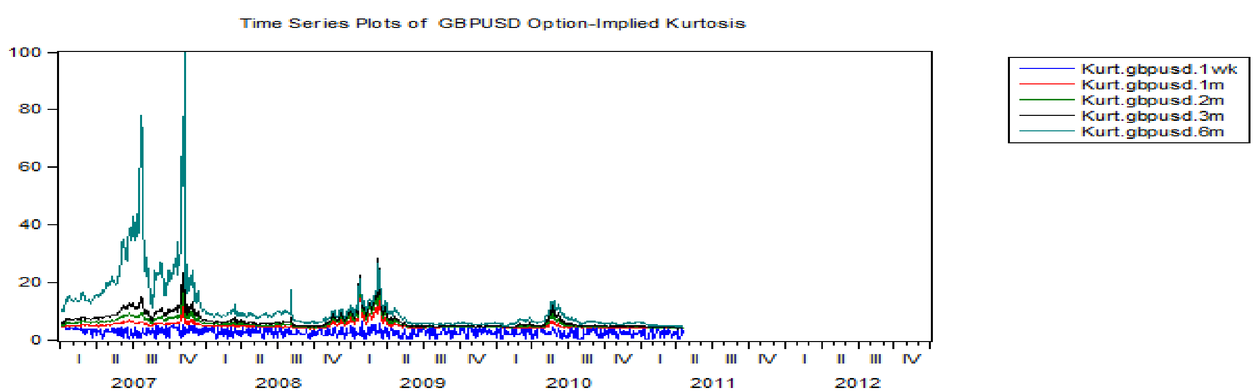
(j) GBPUSD STDEV



(k) GBPUSD SKEWNESS



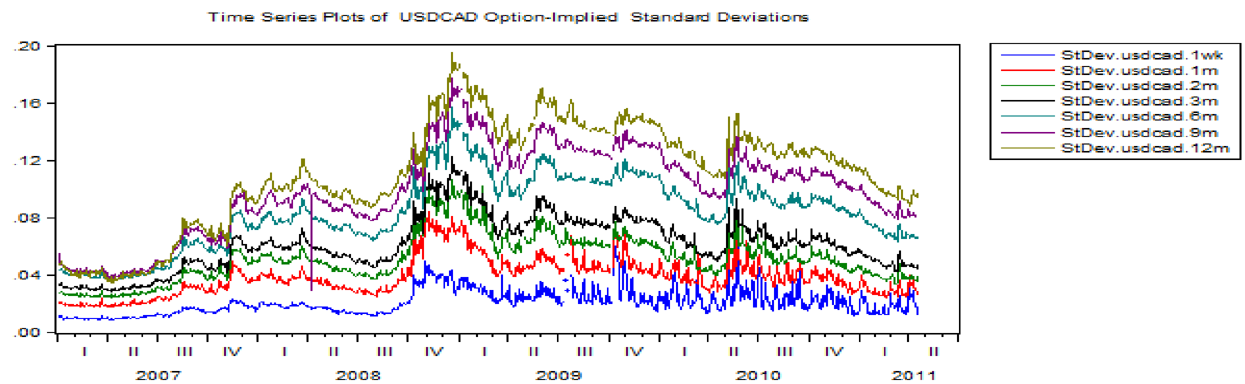
(l) GBPUSD KURTOSIS



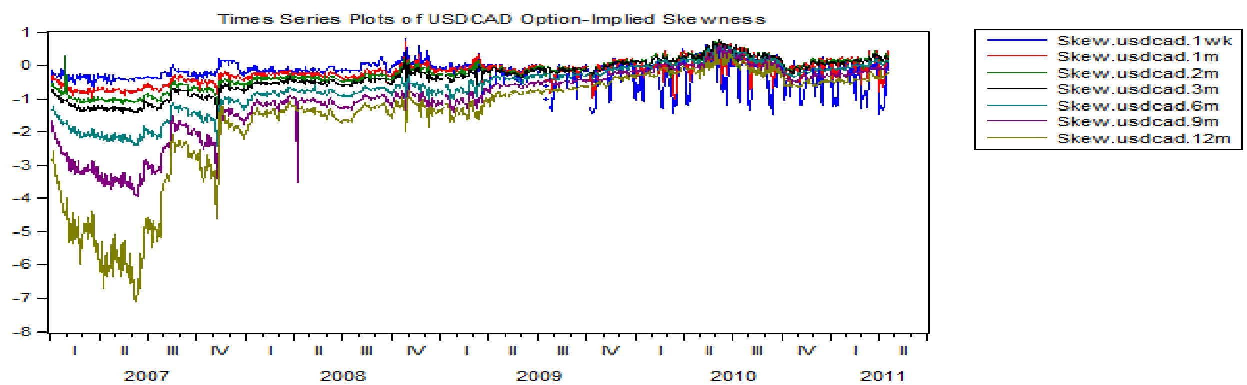
Note: Moments extracted using the methodology developed in Bakshi et al. (2003b).

Figure 2.2: Time Series Evolution Of Option Implied Moments

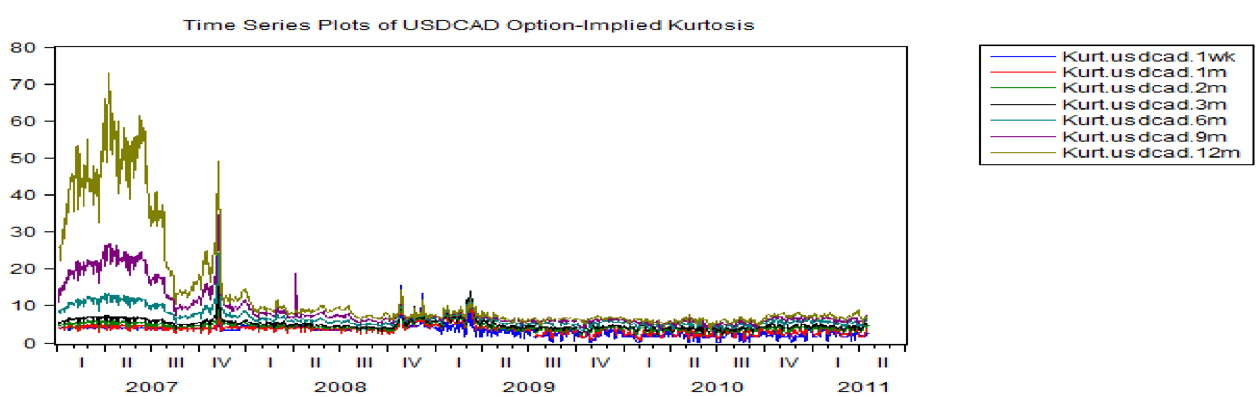
(m) USDCAD STDEV



(n) USDCAD SKEWNESS



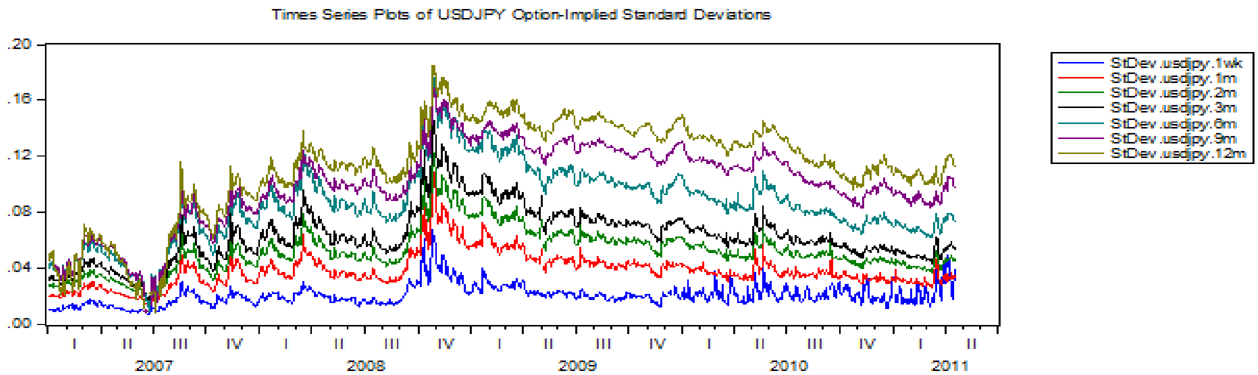
(o) USDCAD KURTOSIS



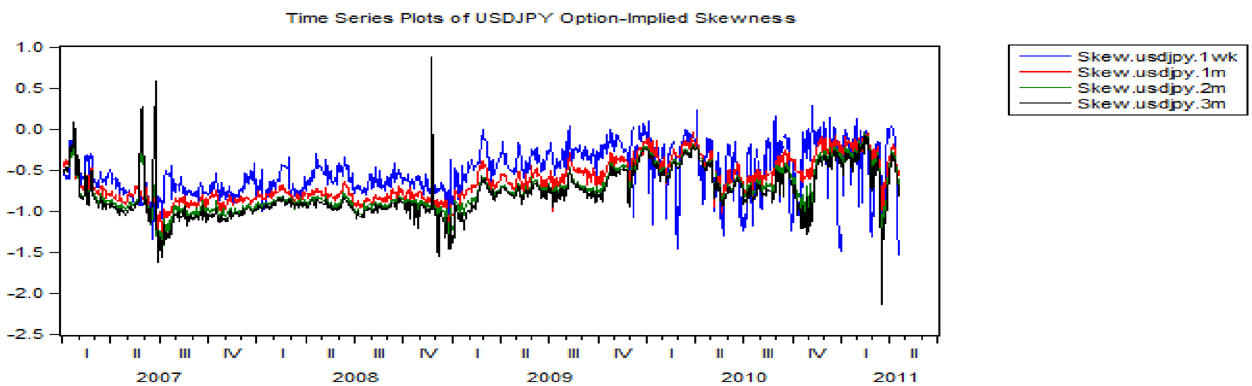
Note: Moments extracted using the methodology developed in Bakshi et al. (2003b).

Figure 2.2: Time Series Evolution Of Option Implied Moments

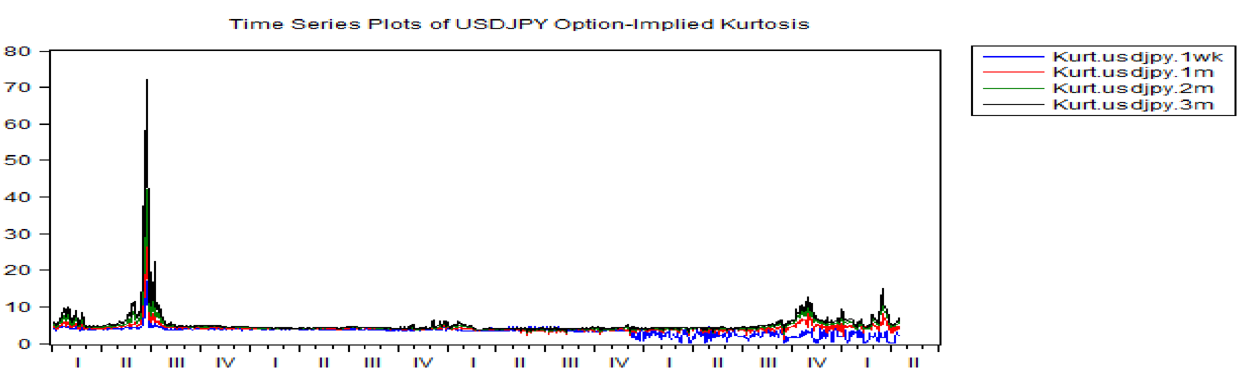
(p) USDJPY STDEV



(q) USDJPY SKEWNESS



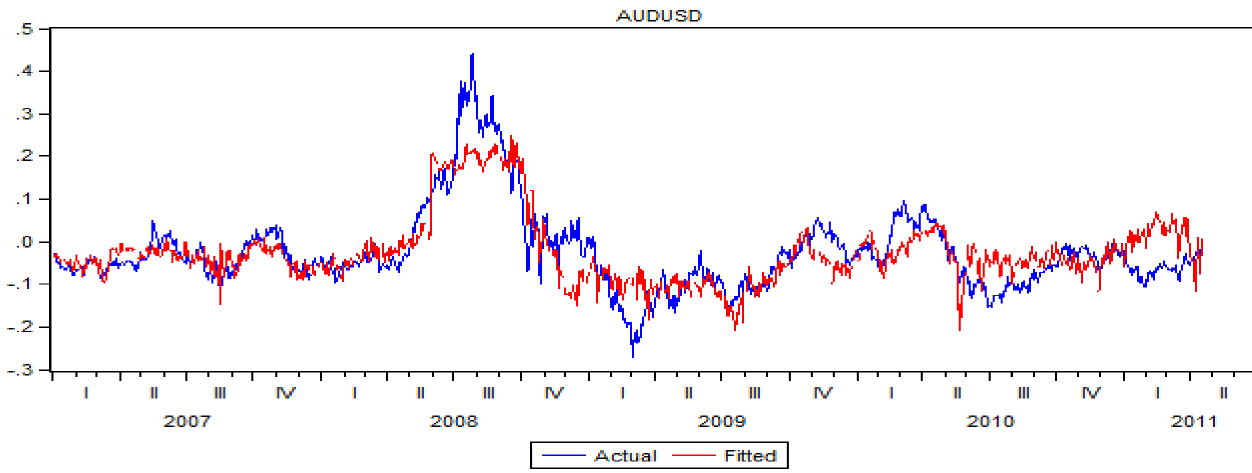
(r) USDJPY KURTOSIS



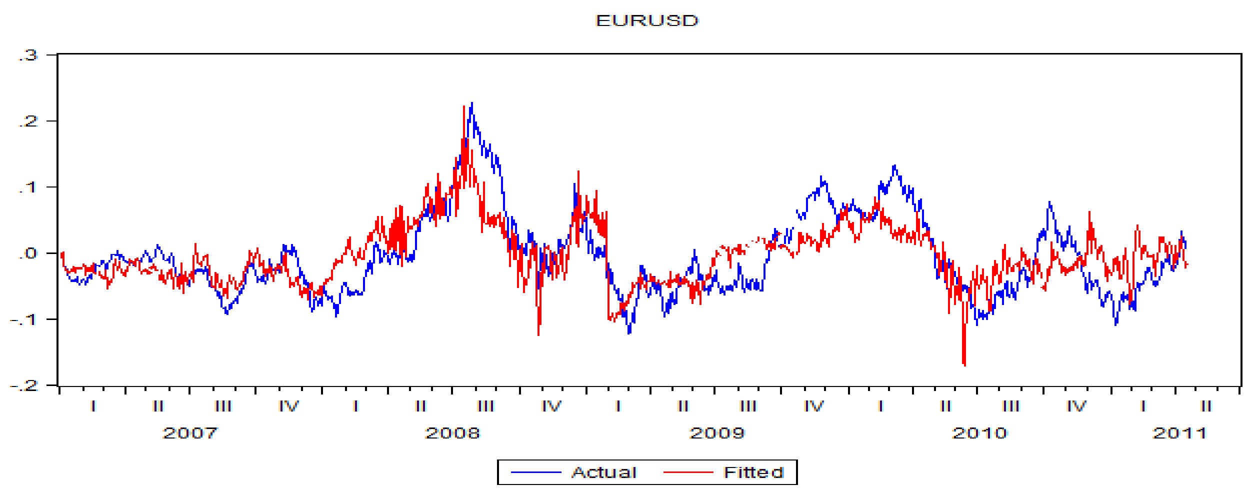
Note: Moments extracted using the methodology developed in Bakshi et al. (2003b).

Figure 2.3: Quarterly FX Excess Returns on Term Structure of 1^{st} to 4^{th} Moments+Break

(a) AUDUSD 3M



(b) EURUSD 3M



(c) GBPUSD 3M

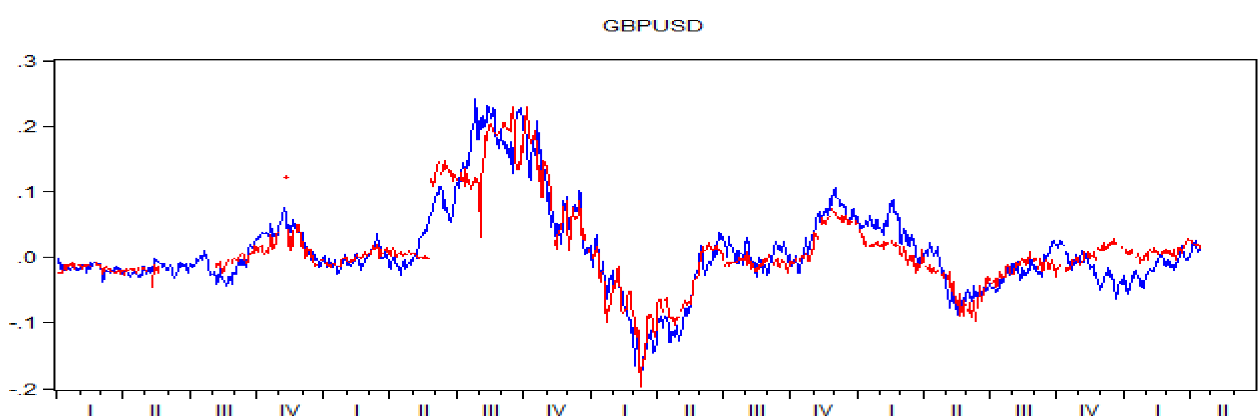
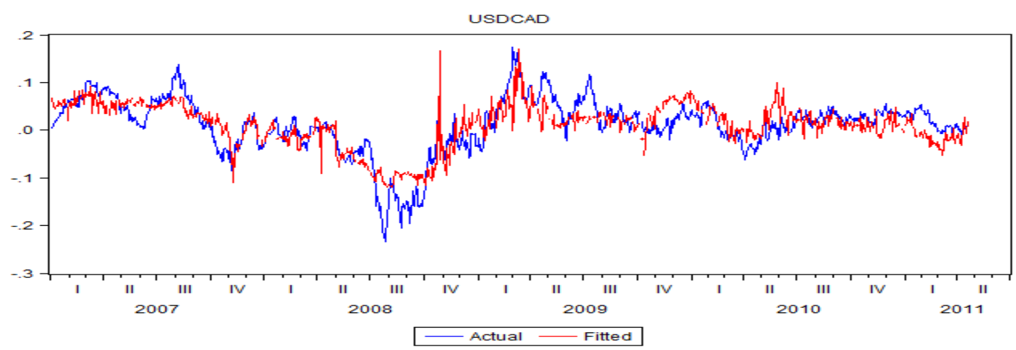
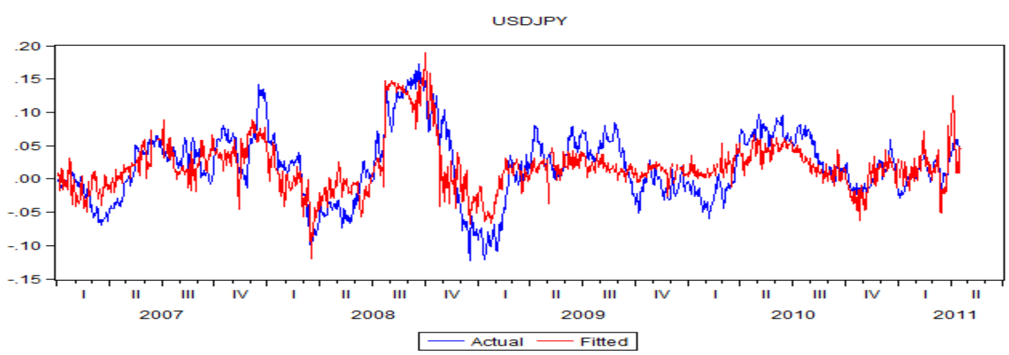


Figure 2.3: Quarterly FX Excess Returns on Term Structure of 1^{st} to 4^{th} Moments+Break

(d) USDCAD 3M



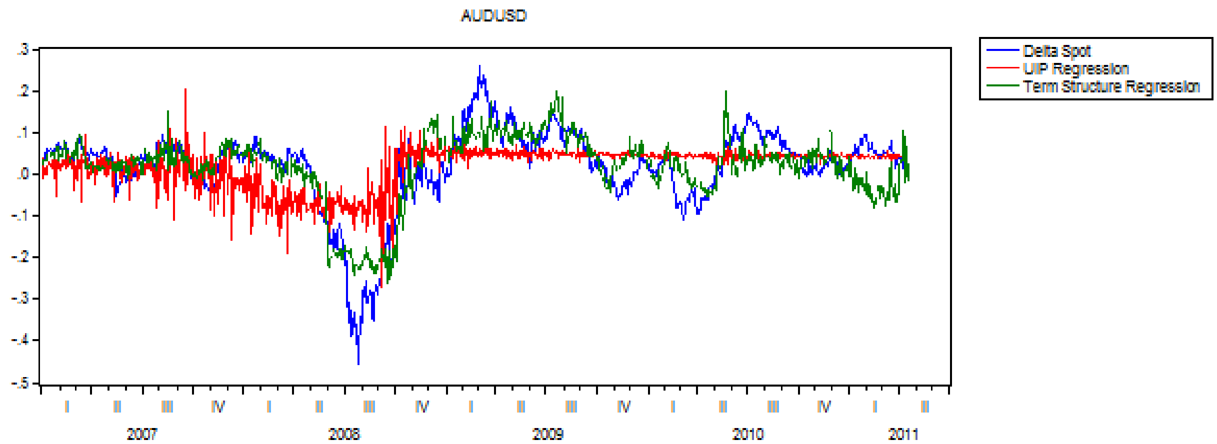
(e) USDJPY 3M



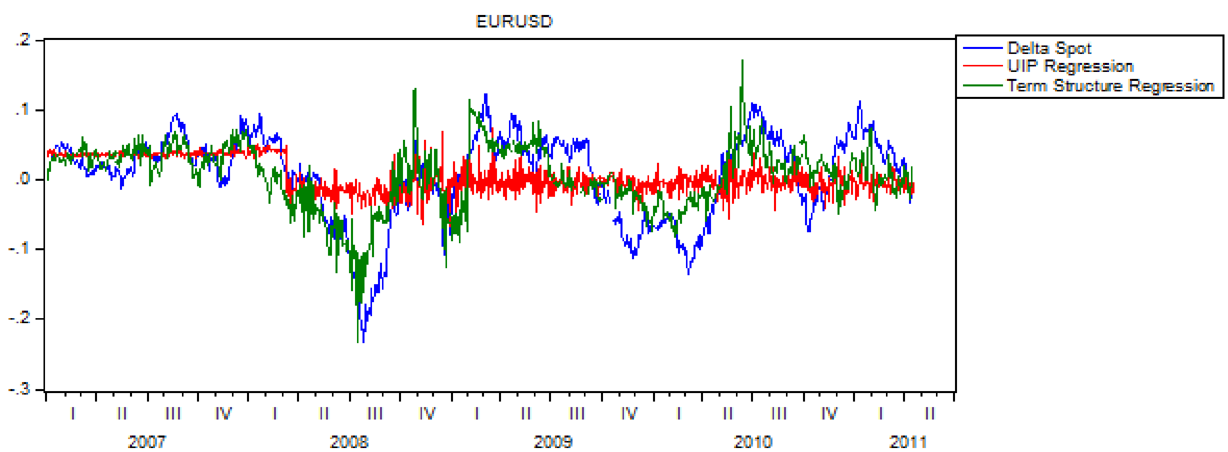
Note: Fitted vs Actual plots from the regression of 3M excess return, as defined in expression (2.2.3), on the first three principal components from the term structure of extracted moments of $\pi_t^Q\left(ln\frac{S_T}{S_t}\right)$ *(Regression specification in expression (2.4.12). Condensed regression results are in column D of table (2.3) .*

Figure 2.4: Quarterly FX Movements on Term Structure of 1^{st} to 4^{th} Moments+Break

(a) AUDUSD 3M RET



(b) EURUSD 3M RET



(c) GBPUSD 3M RET

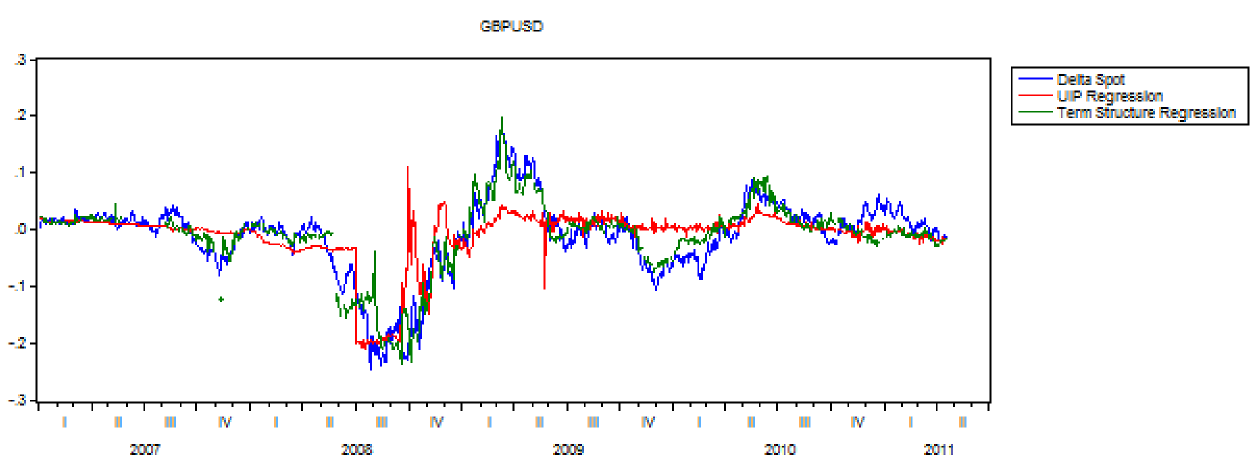
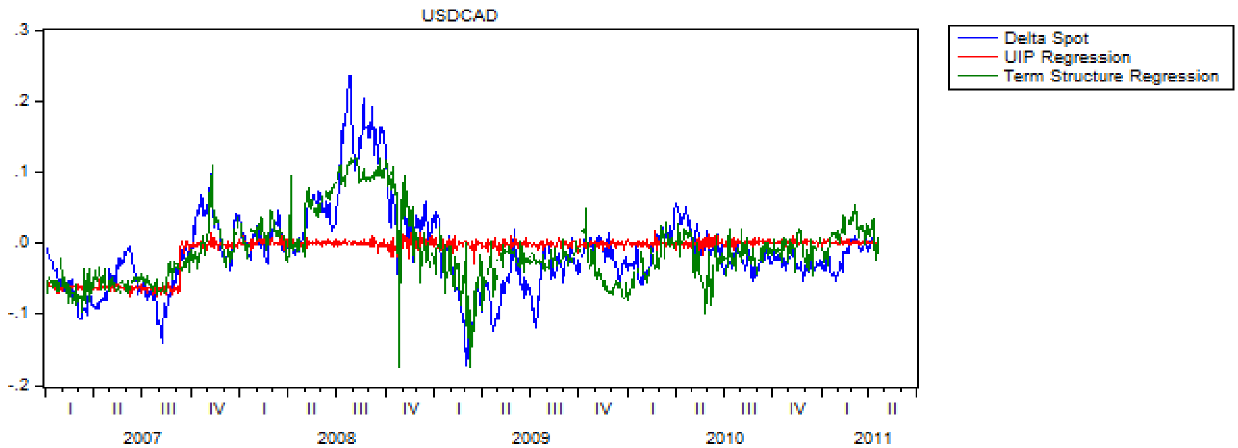
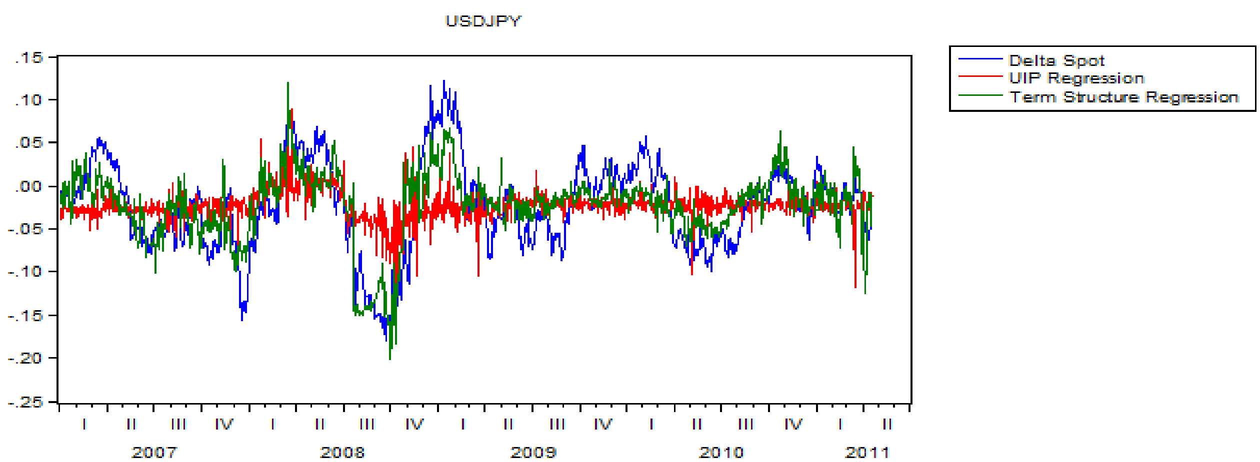


Figure 2.4: Quarterly FX Movements on Term Structure of 1^{st} to 4^{th} Moments+Break

(d) USDCAD 3M RET



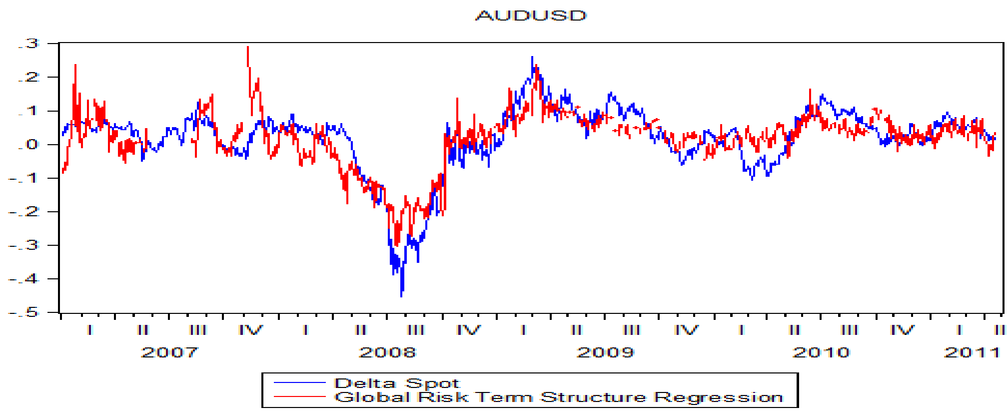
(e) USDJPY 3M RET



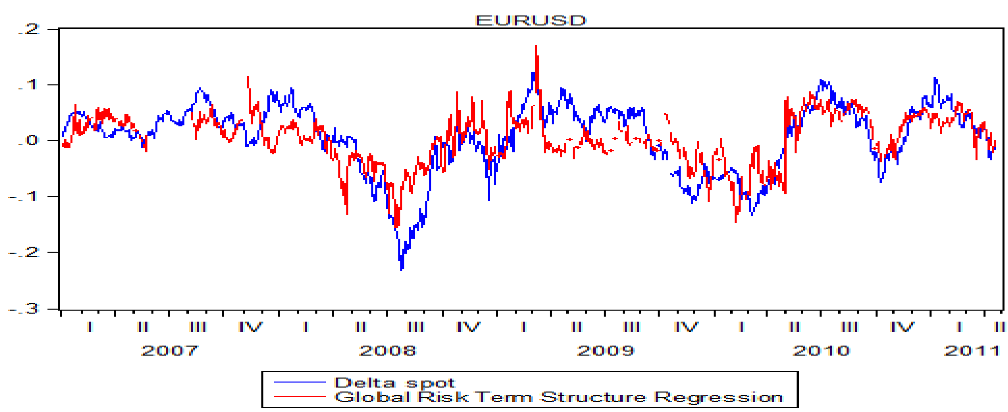
Fitted vs Actual plots from the regression of 3M log $\left(\frac{S_T}{S_t}\right)$ *on the first three principal components from the term structure of extracted moments of* $\pi_t^Q \left(ln\frac{S_T}{S_t}\right)$ *(Regression specification in expression (2.4.4). Condensed regression results are in column D of table (2.4) .*

Figure 2.5: Quarterly FX Movements on Term Structure of Global Risk+Break

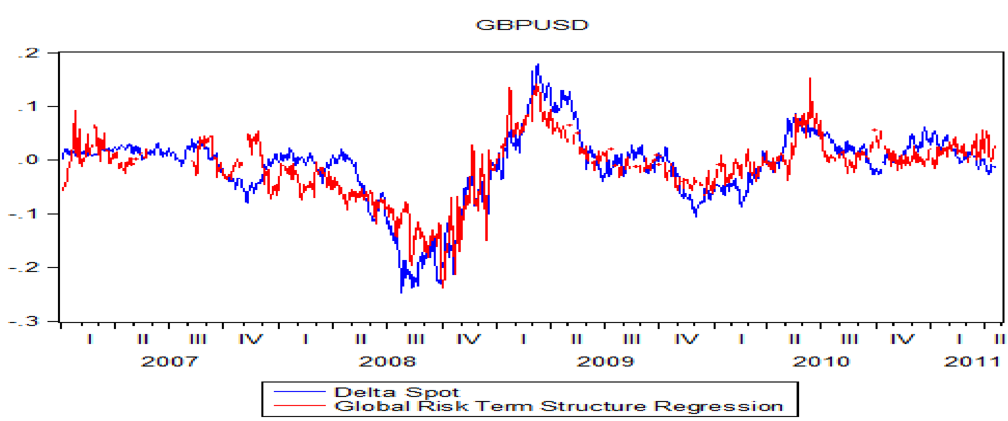
(a) AUDUSD 3M RET



(b) EURUSD 3M RET



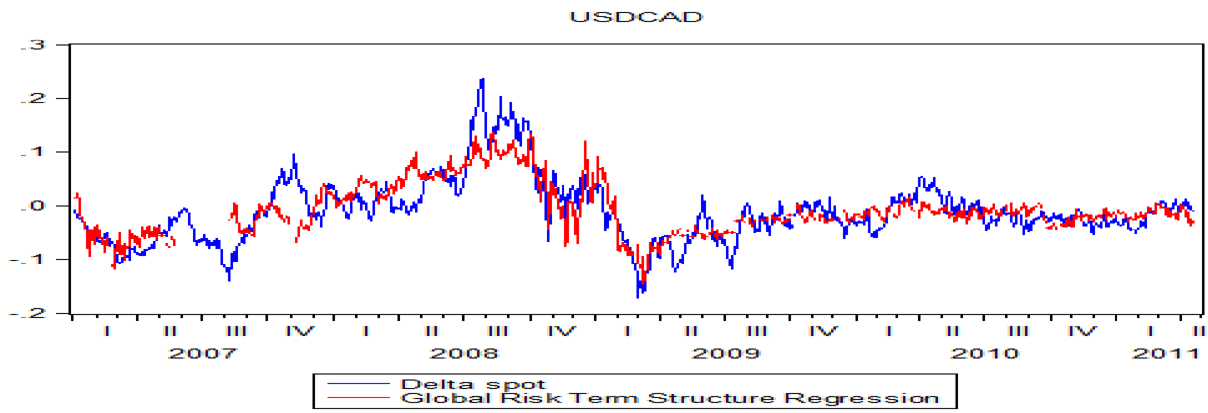
(c) GBPUSD 3M RET



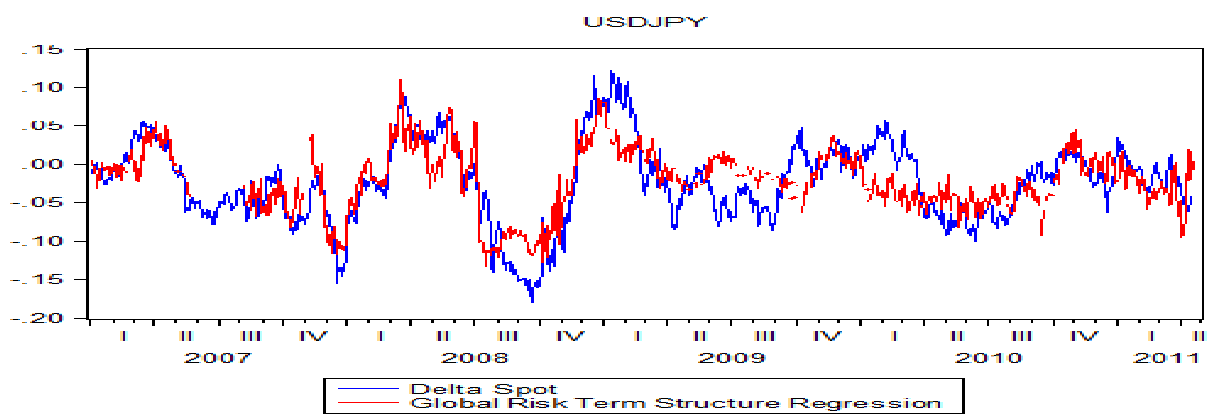
Fitted vs Actual plots from the regression of 3M log $\left(\frac{S_T}{S_t}\right)$ *on the first three principal components from the term structure of extracted moments of* $\pi_t^Q\left(ln\frac{S_T}{S_t}\right)$ *(Regression specification in expression (2.4.4). Condensed regression results are in column D (2.4) .*

Figure 2.5: Quarterly FX Movements on Term Structure of 1^{st} to 4^{th} Moments+Break

(d) USDCAD 3M RET



(e) USDJPY 3M RET



Fitted vs Actual plots from the regression of 3M log $\left(\frac{S_T}{S_t}\right)$ *on the first three principal components from the term structure of extracted moments of* $\pi_t^Q\left(ln\frac{S_T}{S_t}\right)$ *(Regression specification in expression (2.4.4). Condensed regression results are in column D of table (2.4) .*

Table 2.1: O-T-C Market Statistics and Conventions

A. Quoting Conventions in over-the-counter FX Options Market

Symbol	Definition	Base currency	Domestic currency	Positive Skew means
AUDUSD	USD per AUD	AUD	USD	USD depreciation
EURJPY	JPY per EUR	EUR	JPY	EUR depreciation
EURUSD	USD per EUR	EUR	USD	USD depreciation
GBPUSD	USD per GBP	GBP	USD	USD depreciation
USDCAD	CAD per USD	USD	CAD	CAD depreciation
USDJPY	JPY per USD	USD	JPY	JPY depreciation

B. Sample Annualized Implied Volatilities

Tenor	ATM	25D RR	25D VWB	10D RR	10D VWB
1 Week	7.352	-0.495	0.131	-0.847	0.379
1 Month	6.851	-0.347	0.136	-0.584	0.389
2 Month	6.851	-0.366	0.157	-0.619	0.449
3 Month	6.851	-0.396	0.162	-0.663	0.485
6 Month	6.901	-0.426	0.187	-0.703	0.54
9 Month	7.051	-0.446	0.197	-0.743	0.571
12 Month	6.901	-0.426	0.187	-0.703	0.54

C. Average Daily Turnover in FX market (billions)

	1998	2001	2004	2007	2010	2013
Spot FX Transactions	568	386	631	1005	1488	2046
Percentage Change	N/A	-32	63.5	59.3	48.3	37.5
FX Derivatives						
Outright Forwards	128	130	209	362	475	680
FX Swaps	734	656	954	1714	1759	2228
Options and other products	**87**	**60**	119	**212**	**207**	**337**
Percentage Change	N/A	-31	98.3	83	-2.4	62.8
Exchange Traded Derivatives	11	12	26	80	155	160

Note: "ATM" is at-the-money straddle, 25D RR and 10D RR are 25%- and 10%- delta risk reversals respectively; and 25D VWB and 10D VWB are 25%- and 10%- delta Vega-weighted butterflies respectively. See Section (3.3.1) for more details. The numbers in table (3.1C) are from Bank of International Settlements (2013). In table (3.1C) , "other products" refers to "highly levereged transactions and/or trades whose notional amount is variable and where a decomposition into individual plain vanilla components was impractical or impossible" Bank of International Settlements (2013).

Table 2.2: SUMMARY STATISTICS OF OPTION-IMPLED MOMENTS: AUDUSD

(a) AUDUSD

AUDUSD STDEV	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Mean	0.022	0.044	0.044	0.074	0.099	0.112	0.122
Median	0.020	0.041	0.042	0.072	0.098	0.112	0.121
Maximum	0.080	0.114	0.099	0.144	0.170	0.211	0.224
Minimum	0.010	0.019	0.019	0.031	0.039	0.025	0.010
Std. Dev.	0.010	0.018	0.016	0.025	0.034	0.044	0.055
AR(1)	0.970	0.987	0.990	0.999	0.993	0.988	0.986
SKEW							
Mean	-0.371	-0.636	-0.704	-0.979	-1.394	-1.880	-2.081
Median	-0.352	-0.631	-0.693	-0.936	-1.196	-1.513	-1.695
Maximum	0.576	0.043	-0.087	-0.159	-0.540	6.386	371.902
Minimum	-1.461	-2.710	-2.777	-2.568	-3.360	-5.371	-13.301
Std. Dev.	0.214	0.268	0.259	0.367	0.610	1.144	13.235
AR(1)	0.818	0.931	0.927	0.963	0.982	0.939	0.038
KURT							
Mean	3.602	4.424	4.553	5.634	8.088	16.254	164.917
Median	3.528	4.197	4.312	5.045	7.161	8.791	10.176
Maximum	12.881	21.148	19.917	17.426	34.967	1186.148	72716.840
Minimum	2.384	3.481	3.666	3.964	3.918	4.117	4.622
Std. Dev.	0.661	1.191	1.183	1.629	3.610	45.786	2627.969
AR(1)	0.628	0.788	0.781	0.912	0.958	0.419	0.032
XR							
Mean	-0.002	-0.008	-0.016	-0.023	-0.044	-0.059	-0.052
Median	-0.005	-0.016	-0.028	-0.042	-0.078	-0.103	-0.104
Maximum	0.177	0.317	0.348	0.441	0.418	0.383	0.400
Minimum	-0.113	-0.130	-0.195	-0.266	-0.324	-0.397	-0.420
Std. Dev.	0.025	0.052	0.077	0.099	0.155	0.182	0.194
AR(1)	0.754	0.942	0.977	0.985	0.933	0.995	0.995
Observations	1104	1098	1080	1058	992	924	855

Note: "StDev", "Skew", and "Kurt" are the implied standard deviation, skewness, and kurtosis of the risk-neutral distribution of $ln\left(\frac{S_{t+\tau}}{S_t}\right)$.

Table 2.2: SUMMARY STATISTICS OF OPTION-IMPLED MOMENTS: EURJPY

(b) EURJPY

EURJPY							
STDEV							
	1WK	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Mean	0.021674	0.04271	0.058561	0.070497	0.096099	0.11261	0.118433
Median	0.019154	0.039238	0.055391	0.068229	0.097976	0.115059	0.119959
Maximum	0.082968	0.132544	0.15056	0.161267	0.186859	0.202091	0.204448
Minimum	0.008789	0.017555	0.023291	0.025024	0.032846	0.032999	0.027966
Std. Dev.	0.010228	0.018142	0.022714	0.026021	0.034759	0.041768	0.043279
AR(1)	0.972	0.985	0.989	0.99	0.992	0.994	0.992
SKEW							
Mean	-0.473192	-0.751527	-0.917357	-1.060336	-1.265172	-1.409189	-1.648179
Median	-0.455536	-0.730715	-0.878121	-0.979429	-1.175797	-1.308384	-1.56379
Maximum	0.199409	-0.262407	-0.383761	-0.460905	-0.313959	-0.666499	1.285582
Minimum	-1.484654	-2.272107	-2.891797	-3.434762	-3.452745	-3.126212	-4.630548
Std. Dev.	0.204538	0.261852	0.326999	0.402454	0.442298	0.415737	0.501492
Skewness	-0.639309	-1.629437	-1.903247	-2.110969	-1.700785	-1.410536	-1.38116
Kurtosis	4.696886	8.565368	9.317726	9.804044	7.103961	5.374174	11.18123
AR(1)	0.885	0.84	0.912	0.93	0.994	0.939	0.902
KURT							
Mean	4.093253	4.693365	5.340757	5.926772	7.071993	8.467714	11.91333
Median	3.852339	4.184139	4.477222	4.750238	5.404968	6.097588	7.774642
Maximum	17.4046	21.08916	23.74514	26.88282	32.14722	70.07115	238.8331
Minimum	2.86347	3.441621	3.56193	3.734498	3.950154	4.330396	5.138341
Std. Dev.	1.058453	1.822969	2.516841	3.133642	4.172073	6.631089	16.1448
AR(1)	0.665	0.338	0.885	0.912	0.929	0.909	0.829
Observations	1106	1100	1080	1058	992	926	861

Note: "StDev", "Skew", and "Kurt" are the implied standard deviation, skewness, and kurtosis of the risk-neutral distribution of ln $\left(\frac{S_{t+\tau}}{S_t}\right)$.

Table 2.2: SUMMARY STATISTICS OF OPTION-IMPLED MOMENTS: EURUSD

(c) EURUSD

EURUSD STDEV							
	1WK	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Mean	0.016879	0.033992	0.034413	0.057606	0.076927	0.089125	0.091565
Median	0.015343	0.0323	0.034235	0.059432	0.082348	0.095088	0.089599
Maximum	0.045284	0.079987	0.075948	0.119915	0.147176	0.161469	0.163812
Minimum	0.007489	0.014327	0.014973	0.025352	0.033338	0.041093	0.038537
Std. Dev.	0.006722	0.012865	0.01254	0.020112	0.02609	0.031191	0.033787
AR(1)	0.97	0.988	0.991	0.992	0.993	0.995	0.99
SKEW							
Mean	-0.198794	-0.443523	-0.463371	-0.768204	-1.19576	-1.64119	-2.411154
Median	-0.203529	-0.470551	-0.494656	-0.689196	-1.057556	-1.416146	-1.771681
Maximum	0.328861	0.301965	0.262006	0.160658	-0.134049	-0.37118	-0.669719
Minimum	-2.013412	-3.176723	-3.42393	-4.062627	-4.382229	-4.162132	-7.726115
Std. Dev.	0.217068	0.32162	0.329284	0.507657	0.700637	0.93763	1.627093
AR(1)	0.872	0.992	0.961	0.976	0.986	0.992	0.992
KURT							
Mean	4.010456	4.770406	4.955035	6.516796	9.033778	11.89162	19.77612
Median	3.845472	4.33571	4.525413	5.72306	8.22222	10.89346	16.05714
Maximum	18.74862	26.74917	28.74772	32.79291	32.29532	43.0947	73.96947
Minimum	2.630678	3.52634	3.733386	4.291241	5.155273	5.806412	7.715386
Std. Dev.	0.971256	1.669349	1.701551	2.661569	3.571506	5.222871	11.64952
AR(1)	0.708	0.872	0.867	0.925	0.943	0.953	0.962
Observations	1096	1084	1075	1053	988	924	858

Note: "StDev", "Skew", and "Kurt" are the implied standard deviation, skewness, and kurtosis of the risk-neutral distribution of ln $\left(\frac{S_{t+\tau}}{S_t}\right)$.

Table 2.2: SUMMARY STATISTICS OF OPTION-IMPLED MOMENTS: GBPUSD

(d) GBPUSD

GBPUSD STDEV	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Mean	0.016659	0.033842	0.034589	0.058312	0.07714	0.088091	0.098843
Median	0.015414	0.032147	0.03462	0.063454	0.086489	0.102342	0.120972
Maximum	0.042861	0.086263	0.071757	0.106428	0.142224	0.162338	0.180112
Minimum	0.006888	0.013237	0.01456	0.023429	0.021911	0.006785	0.002144
Std. Dev.	0.006616	0.013151	0.012254	0.02001	0.029922	0.039481	0.04768
AR(1)	0.991	0.992	0.994	0.995	0.995	0.985	0.973
SKEW							
Mean	-0.414673	-0.588381	-0.645464	-1.006653	-1.553914	-3.16706	-25.34755
Median	-0.413516	-0.564546	-0.62972	-0.932729	-1.254616	-1.57524	-1.735194
Maximum	0.074597	0.038675	-0.023768	-0.196222	-0.321702	-0.511157	-0.682445
Minimum	-1.677353	-1.980915	-2.025771	-2.596931	-4.66168	-169.0466	-13601.59
Std. Dev.	0.169413	0.259413	0.234075	0.418375	0.921975	7.536254	483.8671
AR(1)	0.917	0.956	0.954	0.964	0.979	0.234	0.072
KURT							
Mean	4.220488	4.920296	5.188567	7.063378	11.72423	435.5905	6205.838
Median	4.080567	4.438236	4.636899	6.127496	8.545569	11.51778	14.23404
Maximum	23.53888	25.57949	27.31958	36.84423	99.40697	281542.7	4471067
Minimum	3.541848	3.696255	3.91905	4.416283	4.732121	5.280972	5.860487
Std. Dev.	1.105758	1.698535	1.808549	3.070666	9.71146	9388.147	152490.1
AR(1)	0.752	0.882	0.883	0.936	0.951	0.098	0.041
Observations	1117	1100	1079	1058	992	925	861

Note:"StDev","Skew", and "Kurt" are the implied standard deviation, skewness, and kurtosis of the risk-neutral distribution of ln $\left(\frac{S_{t+\tau}}{S_t}\right)$.

Table 2.2: SUMMARY STATISTICS OF OPTION-IMPLED MOMENTS: USDCAD

(e) USDCAD

USDCAD							
STDEV							
	1WK	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Mean	0.017912	0.0361	0.036294	0.061299	0.083595	0.097589	0.106553
Median	0.016598	0.034595	0.035397	0.060682	0.08466	0.097017	0.106447
Maximum	0.049693	0.079194	0.074351	0.11589	0.14943	0.171015	0.18983
Minimum	0.008769	0.017519	0.017518	0.028229	0.035458	0.028172	0.03353
Std. Dev.	0.006688	0.012308	0.011545	0.01859	0.026229	0.0334	0.040731
AR(1)	0.977	0.986	0.977	0.984	0.986	0.983	0.985
SKEW							
Mean	0.012461	-0.08054	-0.09118	-0.33315	-0.7241	-1.21782	-1.9646
Median	0.010809	-0.08761	-0.09017	-0.26837	-0.68462	-1.04015	-1.37146
Maximum	0.815055	1.00392	0.969262	0.763276	0.680697	0.610316	-0.06093
Minimum	-0.63518	-0.80116	-0.82152	-1.52709	-2.52086	-3.88847	-7.0237
Std. Dev.	0.25648	0.358043	0.362568	0.524099	0.755894	1.083209	1.738364
AR(1)	0.927	0.985	0.976	0.989	0.993	0.986	0.99
KURT							
Mean	3.734733	4.340128	4.463094	5.352333	7.051105	9.769932	15.7652
Median	3.512644	4.021744	4.168736	4.921509	5.994484	7.256496	8.503259
Maximum	15.5448	16.73578	18.08895	22.22531	32.9993	47.06784	78.01737
Minimum	2.54246	3.434731	3.109827	3.85546	4.37168	4.606047	5.855113
Std. Dev.	0.926606	1.146762	1.175194	1.437642	2.530459	5.755225	15.36327
AR(1)	0.631	0.79	0.757	0.885	0.94	0.969	0.984
Observations	1105	1086	1074	1052	982	915	843

Note: "StDev", "Skew", and "Kurt" are the implied standard deviation, skewness, and kurtosis of the risk-neutral distribution of $ln\left(\frac{S_{t+\tau}}{S_t}\right)$.

Table 2.2: SUMMARY STATISTICS OF OPTION-IMPLED MOMENTS: USDJPY

(f) USDJPY

USDJPY STDEV	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Mean	0.018841	0.038047	0.051943	0.063213	0.08594	0.092971	0.102854
Median	0.017305	0.035546	0.050028	0.061417	0.086524	0.098483	0.111138
Maximum	0.067165	0.118763	0.125911	0.149209	0.178068	0.150092	0.16271
Minimum	0.006846	0.011878	0.01559	0.016492	0.008731	0.009068	0.007129
Std. Dev.	0.007186	0.012963	0.016408	0.020121	0.027025	0.025966	0.031727
AR(1)	0.954	0.974	0.982	0.982	0.986	0.969	0.965
SKEW							
Mean	-0.43506	-0.63303	-0.7744	-0.83337	-0.84734	-1.07009	0.156644
Median	-0.4589	-0.69409	-0.82799	-0.88552	-1.06685	-1.39642	-1.54219
Maximum	0.986929	-0.0404	0.830981	0.867698	101.2098	196.3722	563.1539
Minimum	-1.35088	-2.05881	-2.14246	-2.31887	-3.16534	-3.61909	-4.02461
Std. Dev.	0.298492	0.258659	0.27526	0.298294	3.62774	6.924465	21.71009
AR(1)	0.879	0.942	0.896	0.882	0.515	0.025	0.037
KURT							
Mean	3.841787	4.419539	5.164506	5.683222	12.27508	1306.072	105.4399
Median	3.762949	4.092054	4.30048	4.479744	5.215422	7.518952	8.25259
Maximum	17.45566	28.33674	42.07596	72.08306	3110.937	1161172	32717.97
Minimum	2.80763	3.548593	3.646387	3.766165	4.248792	4.72715	5.104278
Std. Dev.	0.787561	1.503204	2.889401	4.315779	105.6027	38161.83	1534.788
AR(1)	0.584	0.822	0.91	0.964	0.924	0.0006	0.037
Observations	1109	1098	1079	1057	992	926	861

Note: "StDev", "Skew", and "Kurt" are the implied standard deviation, skewness, and kurtosis of the risk-neutral distribution of $ln\left(\frac{S_{t+\tau}}{S_t}\right)$.

Table 2.3: **Higher Moment & Term Structure Predictors of Quarterly FX Excess Returns**

	A	**B**	**C**	**D**
AUDUSD				
# of observations	1122	1120	1106	1039
Adjusted R2	0.33	0.6243	0.5693	0.6621
P(F-stat)	0.00	[0.00,0.00,0.00]	[0.00,0.00,0.00]	[0.00,0.00,0.00,0.00]
Break Date	1/29/2009	6/30/2008	5/12/2008	5/30/2008
EURUSD				
# of observations	1117	1105	1093	1093
Adjusted R2	0.34	0.4895	0.4704	0.5104
P(F-stat)	0.00	[0.00,0.00,0.00]	[0.00,0.00,0.00]	[0.00,0.00,0.00,0.00]
Break Date	2/4/2009	1/29/2009	1/29/2009	2/2/2009
GBPUSD				
# of observations	1121	1055	1050	980
Adjusted R2	0.48	0.7217	0.653	0.8334
P(F-stat)	0.00	[0.00,0.00,0.00]	[0.00,0.00,0.00]	[0.00,0.00,0.00,0.00]
Break Date	10/24/2008	10/24/2008	10/24/2008	5/27/2008
USDCAD				
# of observations	1116	1095	1092	1016
Adjusted R2	0.48	0.5968	0.5824	0.6151
P(F-stat)	0.00	[0.00,0.00,0.00]	[0.00,0.00,0.00]	[0.00,0.00,0.00,0.00]
Break Date	2/5/2009	5/5/2008	5/5/2008	5/2/2008
USDJPY				
# of observations	1121	1107	1099	1099
Adjusted R2	0.2	0.3605	0.3673	0.5668
P(F-stat)	0.00	[0.00,0.00,0.00]	[0.00,0.00,0.00]	[0.00,0.00,0.01,0.00]
Break Date	7/4/2008	7/22/2008	7/21/2008	7/22/2008

Note: In all equations, dependent variable is quarterly excess currency returns, as defined in equation (2.2.3). All regressions are estimated with interactions with a break indicator variable $D1$. *Breakdate for each equation found using Bai and Perron (2003) method. Column **A** is from the matched-frequency regression in equation (2.4.7): Column **B** is regression from column **A** but with 1M and 12M stdev, skew and kurt added as additional regressors (see equation 2.4.10). Three P values are for Wald tests for the null that coefficients on each group of moments [stdev,skew,kurt] are all zero. In column **C** we use the first three principal components extracted from each of stdev,skew and kurt for all tenors(equation 2.4.11). Column **D** is regression from column **C** but with the first three principal components from relative yields (proxying for first moment for the term stucture of first moments) added as additional regressors. In column **D** (equation 2.4.12), P values are for the null that coefficients on each group of principal components for [mean, stdev, skew , kurtosis] are jointly zero. Actual vs Fitted plots for the regressions in column **D** can be found in figures 2.3(a)-2.3(e).*

Table 2.4: **Higher Moment and Term Structure Predictors of Quarterly FX Returns**

	A	**B**	**C**	**D**
AUDUSD				
# of observations	1122	1122	1054	1039
Adjusted R2	0.2656	0.3457	0.564	0.6704
P(F-stat)	0.00	0.00	0.00	[0.00,0.00,0.00,0.00]
Break Date	10/6/2008	1/29/2009	1/13/2009	5/30/2008
EURUSD				
# of observations	1117	1117	1093	1093
Adjusted R2	0.148	0.366	0.3996	0.5302
P(F-stat)	0.00	0.00	0.00	[0.00,0.00,0.00,0.00]
Break Date	3/10/2008	2/4/2009	5/16/2008	2/2/2008
GBPUSD				
# of observations	1116	1121	1045	980
Adjusted R2	0.5254	0.6682	0.6349	0.839
P(F-stat)	0.00	0.00	0.00	[0.00,0.00,0.00,0.00]
Break Date	7/1/2008	6/30/2008	7/7/2008	5/27/2008
USDCAD				
# of observations	1121	1116	1037	1016
Adjusted R2	0.1561	0.493	0.5359	0.6234
P(F-stat)	0.00	0.00	0.00	[0.00,0.00,0.00,0.00]
Break Date	9/11/2007	2/5/2009	10/15/2008	5/2/2008
USDJPY				
# of observations	1121	1121	1112	1099
Adjusted R2	0.1033	0.2619	0.2846	0.5774
P(F-stat)	0.00	0.00	0.00	[0.00,0.00,0.01,0.00]
Break Date	7/4/2008	7/4/2008	7/4/2008	7/22/2008

Note: In all equations, dependent variable is quarterly currency returns,ln $\left(\frac{S_{t+3M}}{S_t}\right)$ *. All regressions are estimated with interactions with a break indicator variable* $D1$*. Breakdate for each equation found using Bai and Perron (2003) method. Column **A** is from the standard UIP regression (equation (2.4.1)) :*

$$s^i_{t+\tau} - s^i_t = \alpha_0 + \alpha_1 * D1^{i,\tau} + \beta_1(f^{t+\tau,i}_t - s^i_t) + \beta_2 D1^{i,\tau} * (f^{t+\tau,i}_t - s^i_t) + \epsilon^i_{t+\tau}$$

*P values in column **A** are for the null hypothesis that* $\beta_1 = \beta_2 = 0$ *. Column **B** is column **A** with quarterly stdev, skew and kurt also added(equation (2.4.2,with break) In Column **C** (equation (2.4.3)) , we extract the first 3 Principal components from relative yields and use them as regressors (term structure of first moments as regressors). In column **D** (equation 2.4.4) we extract principal components from each of stdev,skew, kurtosis, and use them as additional regressors from the specification in column **C** (Term structure of* 1^{st}*-*4^{th} *moments). Actual vs Fitted plots for specification in columns **A** and **D** are in figures 2.4(a)-2.4(e).*

Table 2.5: Global Risk XR Regressions

	A	B	C	D
	Matched Frequency XR	Term Structure XR	Matched Frequency RET	Term Structure RET
AUDUSD				
# of obs.	1109	976	1109	976
Adj. R2	0.614	0.632	0.622	0.64
P(F-stat)	0	0	0	0
Break date	5/9/2008	10/6/2008	5/9/2008	10/6/2008
EURUSD				
# of obs.	1109	976	1109	976
Adj. R2	0.452	0.486	0.255	0.495
P(F-stat)	0	0	0	0
Break date	4/16/2010	5/3/2010	10/22/2009	5/3/2010
GBPUSD				
# of obs.	1109	976	1109	976
Adj. R2	0.591	0.664	0.602	0.674
P(F-stat)	0	0	0	0
Break date	10/24/2008	12/17/2008	10/24/2008	12/17/2008
USDCAD				
# of obs.	1109	976	1109	976
Adj. R2	0.651	0.638	0.656	0.64
P(F-stat)	0	0	0	0
Break date	7/4/2008	1/30/2009	7/4/2008	1/30/2009
USDJPY				
# of obs.	1109	976	1109	976
Adj. R2	0.552	0.572	0.556	0.573
P(F-stat)	0	0	0	0
Break date	7/4/2008	7/4/2008	7/4/2008	7/4/2008

*Note: In column **A**, for each quarterly excess return, we use the first three principal components extracted from the 3-month risk-neutral moments of all currencies as regressors. In column **B**, For each quarterly excess return, we use the first three principal components extracted from each moments for all tenors and all currencies as regressors. In column **C**, for each quarterly exchange rate change, we use the first three principal components extracted from the 3-month risk-neutral moments of all currencies as regressors. In column **D**, for each quarterly exchange rate change , we use the first three principal components extracted from each moments for all tenors and all currencies as regressors. Newey-West standard deviations are reported in brackets, with asterisks indicating significance at 1% (***), 5% (**), and 10% (*) level. F-stats and P value below are based on the Wald test of the null that the coefficients on all principal components are zero.*

Table 2.6: FX EXCESS RETURNS MATCHED FREQUENCY OLS REGRESSIONS

(a) AUDUSD

Eq Name:	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Dep. Var:	XR	XR	XR	XR	XR	XR	XR
C	0.022	0.06	0.11	0.133	0.779	0.403	-0.17
	[0.0089]**	[0.0220]***	[0.0342]***	[0.0497]***	[0.2588]***	[0.1084]***	[0.0716]**
D1	-0.018	0.015	0.054	0.133	-0.594	0.019	0.611
	[0.0100]*	[0.0328]	[0.0498]	[0.0671]**	[0.2613]**	[0.1219]	[0.1012]***
STDEV	0.082	0.672	0.393	-0.135	-4.031	0.172	4.111
	[0.1959]	[0.2120]***	[0.2325]*	[0.2968]	[1.9442]**	[0.8341]	[0.5854]***
SKEW	0.02	0.064	0.095	0.158	0.409	0.394	0.063
	[0.0088]**	[0.0283]**	[0.0414]**	[0.0641]**	[0.0541]***	[0.0224]***	[0.0183]***
KURT	-0.004	-0.008	-0.005	0.012	0.028	0.041	0.005
	[0.0020]*	[0.0068]	[0.0090]	[0.0129]	[0.0174]	[0.0030]***	[0.0014]***
D1*AUDUSD	-0.33	-2.366	-2.896	-2.899	1.94	-3.376	-7.133
	[0.2228]	[0.4441]***	[0.4650]***	[0.4956]***	[1.9658]	[0.8902]***	[0.6805]***
D1*SKEW	-0.027	-0.056	-0.057	-0.092	-0.429	-0.371	0.021
	[0.0102]***	[0.0317]*	[0.0463]	[0.0687]	[0.0650]***	[0.0413]***	[0.0412]
D1*KURT	0.001	0.004	0.002	-0.017	-0.038	-0.05	-0.004
	[0.0023]	[0.0073]	[0.0095]	[0.0136]	[0.0188]**	[0.0075]***	[0.0062]
Observations:	1109	1120	1122	1122	1122	1119	1122
Adj. R-squared:	0.0535	0.2429	0.2997	0.3215	0.5973	0.8029	0.8158
Prob(F-stat)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Break Date	3/2/2009	2/17/2009	2/2/2009	1/29/2009	10/6/2008	8/29/2008	8/1/2008

Note: "XR" is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{2,\tau} skew^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{3,\tau} kurt^{t+\tau}_t + \gamma_{4,\tau} stdev^{i,t+\tau}_t + \gamma_{5,\tau} skew^{i,t+\tau}_t + \gamma_{6,\tau} kurt^{i,t+\tau}_t + \epsilon_{i,t+\tau}.$$

D1 = break date selected by Bai and Perron (2003) test, allowing for maximum of one break. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0$. *Newey-West Standard errors are reported in brackets. Asterisks indicate significance at 1 % (***), 5% (**), and 10% (*) level.*

Table 2.6: FX EXCESS RETURNS MATCHED FREQUENCY OLS REGRESSIONS

(b) EURJPY

Eq Name:	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Dep. Var:	XR	XR	XR	XR	XR	XR	XR
C	-0.007	-0.021	-0.062	-0.122	-0.087	-0.066	-0.08
	[0.0057]	[0.0131]	[0.0166]***	[0.0306]***	[0.0207]***	[0.0241]***	[0.0356]**
D1	0.015	0.08	0.18	0.287	0.65	0.812	0.705
	[0.0080]*	[0.0205]***	[0.0311]***	[0.0475]***	[0.0483]***	[0.0421]***	[0.0549]***
STDEV	0.356	-0.927	-0.48	-2.331	-0.482	-0.975	0.07
	[0.2487]	[0.3203]***	[0.3608]	[0.4297]***	[0.3192]	[0.3360]***	[0.3748]
SKEW	0.005	-0.028	-0.008	-0.26	-0.073	-0.074	-0.026
	[0.0053]	[0.0166]*	[0.0259]	[0.0443]***	[0.0212]***	[0.0205]***	[0.0162]
KURT	0.001	0.004	0.013	-0.006	0.001	0	0
	[0.0011]	[0.0028]	[0.0036]***	[0.0041]	[0.0011]	[0.0004]	[0.0002]
D1*AUDUSD	-0.508	0.389	-0.926	0.687	-2.645	-2.237	-2.241
	[0.2946]*	[0.4215]	[0.4913]*	[0.6062]	[0.4532]***	[0.3877]***	[0.4146]***
D1*SKEW	-0.005	-0.065	-0.2	0.074	0.258	0.267	0.18
	[0.0064]	[0.0330]**	[0.0576]***	[0.0752]	[0.0450]***	[0.0258]***	[0.0257]***
D1*KURT	-0.003	-0.024	-0.049	-0.028	0.01	0.004	0.004
	[0.0016]*	[0.0049]***	[0.0087]***	[0.0104]***	[0.0056]*	[0.0013]***	[0.0013]***
Observations:	1111	1122	1122	1122	1122	1122	1122
Adj. R-squared:	0.0199	0.1812	0.3135	0.4294	0.6292	0.7392	0.5976
Prob(F-stat)	0.64	0.00	0.00	0.00	0.00	0.00	0.00
Break Date	10/22/2008	8/8/2008	8/8/2008	8/8/2008	4/1/2008	1/4/2008	10/4/2007

Note: "XR" is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + D1^{i,\tau} + \gamma_{00,\tau} D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

D1 = break date selected by Bai and Perron (2003) test, allowing for maximum of one break. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0$. *Newey-West Standard errors are reported in brackets. Asterisks indicate significance at 1 % (***), 5% (**), and 10% (*) level.*

Table 2.6: FX EXCESS RETURNS MATCHED FREQUENCY OLS REGRESSIONS

(c) EURUSD

Eq Name:	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Dep. Var:	XR	XR	XR	XR	XR	XR	XR
C	-0.011	0.063	0.125	0.132	0.151	-0.099	-0.709
	[0.0051]**	[0.0295]**	[0.0387]***	[0.0426]***	[0.0366]***	[0.0774]	[0.1240]***
D1	0.007	-0.031	-0.028	0.062	0.206	0.531	1.07
	[0.0060]	[0.0346]	[0.0477]	[0.0573]	[0.0566]***	[0.0948]***	[0.1362]***
STDEV	0.66	-0.046	-0.487	-0.861	-1.216	3.596	9.624
	[0.3078]**	[0.3193]	[0.2954]*	[0.2385]***	[0.4558]***	[0.8086]***	[1.3159]***
SKEW	0.005	0.078	0.119	0.125	-0.018	0.102	0.004
	[0.0037]	[0.0184]***	[0.0220]***	[0.0205]***	[0.0210]	[0.0129]***	[0.0128]
KURT	0.001	-0.003	-0.001	0.005	-0.021	0.009	0.005
	[0.0007]	[0.0035]	[0.0026]	[0.0026]**	[0.0048]***	[0.0008]***	[0.0008]***
D1*AUDUSD	-0.612	-0.476	-0.705	-1.441	-2.194	-6.123	-10.893
	[0.3149]*	[0.4404]	[0.5252]	[0.5641]**	[0.6068]***	[0.9402]***	[1.3655]***
D1*SKEW	-0.008	-0.092	-0.133	-0.134	0.084	-0.033	0.073
	[0.0042]*	[0.0201]***	[0.0243]***	[0.0241]***	[0.0240]***	[0.0287]	[0.0244]***
D1*KURT	0	-0.003	-0.009	-0.016	0.023	-0.019	-0.017
	[0.0011]	[0.0042]	[0.0034]**	[0.0037]***	[0.0051]***	[0.0049]***	[0.0044]***
Observations:	1101	1108	1117	1117	1118	1120	1119
Adj. R-squared:	0.0283	0.1465	0.256	0.34	0.5075	0.6878	0.6529
Prob(F-stat)	0.21	0.00	0.00	0.00	0.00	0.00	0.00
Break Date	10/21/2008	2/13/2009	1/19/2009	2/4/2009	2/26/2008	8/11/2008	8/8/2011

Note: "XR" is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{2,\tau} skew^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{3,\tau} kurt^{t+\tau}_t + \gamma_{4,\tau} stdev^{i,t+\tau}_t + \gamma_{5,\tau} skew^{i,t+\tau}_t + \gamma_{6,\tau} kurt^{i,t+\tau}_t + \epsilon_{i,t+\tau}.$$

D1 = break date selected by Bai and Perron (2003) test, allowing for maximum of one break. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0$. *Newey-West Standard errors are reported in brackets. Asterisks indicate significance at 1 % (***), 5% (**), and 10% (*) level.*

Table 2.6: FX EXCESS RETURNS MATCHED FREQUENCY OLS REGRESSIONS

(d) GBPUSD

Eq Name:	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Dep. Var:	XR	XR	XR	XR	XR	XR	XR
C	-0.005	-0.058	0.085	-0.039	0.067	-0.242	-0.063
	[0.0045]	[0.0218]***	[0.0231]***	[0.0432]	[0.0861]	[0.0426]***	[0.0294]**
D1	0.01	0.047	0.009	-0.021	-0.035	0.447	0.348
	[0.0068]	[0.0234]**	[0.0325]	[0.0455]	[0.0925]	[0.0543]***	[0.0560]***
STDEV	0.459	2.705	0.534	2.861	2.308	6.538	4.242
	[0.2319]**	[0.4286]***	[0.2153]**	[0.4514]***	[0.9282]**	[0.7318]***	[0.4385]***
SKEW	0.004	0.041	0.067	0.078	0.083	-0.005	0
	[0.0039]	[0.0168]**	[0.0241]***	[0.0260]***	[0.0232]***	[0.0024]**	[0.0001]
KURT	0.001	0.006	-0.003	0.007	0.004	0	0
	[0.0008]	[0.0020]***	[0.0029]	[0.0017]***	[0.0010]***	[0.0000]*	[0.0000]
D1*AUDUSD	-0.429	-1.862	0.666	-1.085	-1.463	-6.963	-5.302
	[0.2872]	[0.4747]***	[0.5100]	[0.5168]**	[1.0195]	[0.7824]***	[0.5746]***
D1*SKEW	-0.003	-0.048	-0.113	-0.111	-0.06	0.062	0.071
	[0.0051]	[0.0242]**	[0.0310]***	[0.0329]***	[0.0309]*	[0.0161]***	[0.0157]***
D1*KURT	-0.003	-0.012	-0.037	-0.023	-0.02	-0.013	-0.007
	[0.0012]***	[0.0026]***	[0.0069]***	[0.0039]***	[0.0037]***	[0.0025]***	[0.0022]***
Observations:	1116	1122	1122	1121	1122	1116	1056
Adj. R-squared:	0.0554	0.2825	0.4025	0.4848	0.5927	0.7281	0.7338
Prob(F-stat)	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Break Date	11/11/2008	10/22/2008	3/19/2009	10/24/2008	10/21/2008	8/22/2008	8/8/2008

Note: "XR" is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

D1 = break date selected by Bai and Perron (2003) test, allowing for maximum of one break. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0$. *Newey-West Standard errors are reported in brackets. Asterisks indicate significance at 1 % (***), 5% (**), and 10% (*) level.*

Table 2.6: FX EXCESS RETURNS MATCHED FREQUENCY OLS REGRESSIONS

(e) USDCAD

Eq Name:	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Dep. Var:	XR	XR	XR	XR	XR	XR	XR
C	0.027	-0.137	-0.124	-0.224	0.419	0.419	0.526
	[0.0112]**	[0.0435]***	[0.0388]***	[0.0500]***	[0.0609]***	[0.1517]***	[0.0640]***
D1	-0.025	0.14	0.07	0.148	-0.853	-0.792	-0.834
	[0.0127]**	[0.0445]***	[0.0418]*	[0.0526]***	[0.0671]***	[0.1554]***	[0.0740]***
STDEV	-1.512	3.496	0.242	1.135	-4.887	-6.294	-6.563
	[0.5275]***	[0.8439]***	[0.3404]	[0.4719]**	[0.6124]***	[1.3438]***	[0.5914]***
SKEW	0.003	-0.013	-0.088	-0.155	0.048	0.004	0.048
	[0.0091]	[0.0213]	[0.0220]***	[0.0351]***	[0.0258]*	[0.0398]	[0.0135]***
KURT	-0.001	0.017	0.012	0.007	-0.003	-0.001	0.002
	[0.0025]	[0.0042]***	[0.0061]*	[0.0089]	[0.0044]	[0.0044]	[0.0017]
D1*AUDUSD	1.447	-3.398	0.301	-0.558	7.907	8.611	8.508
	[0.5512]***	[0.8679]***	[0.4093]	[0.5129]	[0.6574]***	[1.3592]***	[0.6118]***
D1*SKEW	0.001	0.05	0.056	0.122	0.109	0.043	-0.043
	[0.0094]	[0.0233]**	[0.0248]**	[0.0363]***	[0.0296]***	[0.0421]	[0.0170]**
D1*KURT	0.002	-0.018	0.001	0.008	0.039	0.029	0.015
	[0.0028]	[0.0045]***	[0.0064]	[0.0090]	[0.0061]***	[0.0060]***	[0.0050]***
Observations:	1110	1110	1116	1116	1113	1111	1105
Adj. R-squared:	0.0792	0.1319	0.3255	0.4806	0.6812	0.7595	0.7929
Prob(F-stat)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Break Date	10/21/2008	10/15/2007	2/24/2009	2/5/2009	2/27/2008	8/8/2008	7/25/2008

Note: "XR" is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{2,\tau} skew^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{3,\tau} kurt^{t+\tau}_t + \gamma_{4,\tau} stdev^{i,t+\tau}_t + \gamma_{5,\tau} skew^{i,t+\tau}_t + \gamma_{6,\tau} kurt^{i,t+\tau}_t + \epsilon_{i,t+\tau}.$$

D1 = break date selected by Bai and Perron (2003) test, allowing for maximum of one break. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0.$ *Newey-West Standard errors are reported in brackets. Asterisks indicate significance at 1 % (***), 5% (**), and 10% (*) level.*

Table 2.6: FX EXCESS RETURNS MATCHED FREQUENCY OLS REGRESSIONS

(f) USDJPY

Eq Name:	**1WK**	**1M**	**2M**	**3M**	**6M**	**9M**	**12M**
Dep. Var:	XR	XR	XR	XR	XR	XR	XR
C	0	-0.014	-0.042	-0.003	0.057	0.131	0.13
	[0.0057]	[0.0138]	[0.0134]***	[0.0242]	[0.0256]**	[0.0202]***	[0.0091]***
D1	0.024	0.145	0.243	0.172	0.24	0.169	0.155
	[0.0082]***	[0.0260]***	[0.0313]***	[0.0448]***	[0.0401]***	[0.0298]***	[0.0288]***
STDEV	0.082	0.356	0.727	-0.761	-0.945	-1.651	-1.005
	[0.1894]	[0.2029]*	[0.2008]***	[0.3523]**	[0.2229]***	[0.2829]***	[0.1620]***
SKEW	0.004	-0.005	-0.01	-0.043	-0.026	-0.016	-0.001
	[0.0073]	[0.0167]	[0.0121]	[0.0146]***	[0.0154]*	[0.0081]**	[0.0003]**
KURT	0.001	0.001	0.003	0.002	0.001	0	0
	[0.0006]	[0.0007]**	[0.0008]***	[0.0005]***	[0.0005]*	[0.0002]**	[0.0000]**
D1*AUDUSD	-0.828	-2.11	-3.25	-0.624	-0.962	0.345	-0.112
	[0.2876]***	[0.4784]***	[0.4696]***	[0.5732]	[0.3293]***	[0.3133]	[0.2243]
D1*SKEW	-0.002	-0.001	-0.04	-0.015	0.002	0.066	0.008
	[0.0080]	[0.0201]	[0.0190]**	[0.0232]	[0.0214]	[0.0145]***	[0.0093]
D1*KURT	-0.003	-0.016	-0.021	-0.02	-0.017	-0.005	-0.009
	[0.0012]***	[0.0023]***	[0.0025]***	[0.0030]***	[0.0027]***	[0.0012]***	[0.0014]***
Observations:	1114	1120	1121	1121	1122	1116	1109
Adj. R-squared:	0.0339	0.1238	0.2201	0.2044	0.3829	0.4531	0.3254
Prob(F-stat)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Break Date	1/20/2009	1/8/2009	12/15/2008	7/4/2008	4/23/3008	1/4/2008	10/4/2007

Note: "XR" is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{2,\tau} skew^{i,t+\tau}_t + D1^{i,\tau} * \gamma_{3,\tau} kurt^{t+\tau}_t + \gamma_{4,\tau} stdev^{i,t+\tau}_t + \gamma_{5,\tau} skew^{i,t+\tau}_t + \gamma_{6,\tau} kurt^{i,t+\tau}_t + \epsilon_{i,t+\tau}.$$

D1 = break date selected by Bai and Perron (2003) test, allowing for maximum of one break. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0$. Newey-West Standard errors are reported in brackets. Asterisks indicate significance at 1 % (***), 5% (**), and 10% (*) level.

Table 2.7: FX QUARTERLY EXCESS RETURNS MATCHED FREQUENCY ROBUST LS

Eq Name:	AUDUSD	EURJPY	EURUSD	GBPUSD	USDCAD	USDJPY
Dep. Var:	XR	XR	XR	XR	XR	XR
C	-0.043	-0.1	0.075	-0.14	-0.126	-0.005
	[0.0110]***	[0.0137]***	[0.0171]***	[0.0134]***	[0.0139]***	[0.0126]
D3M	0.297	0.23	0.095	0.079	0.053	0.224
	[0.0209]***	[0.0187]***	[0.0252]***	[0.0148]***	[0.0168]***	[0.0215]***
STDEV	0.253	-1.904	-0.588	2.685	0.015	-0.742
	[0.0850]***	[0.2153]***	[0.1213]***	[0.1857]***	[0.1258]	[0.1556]***
SKEW	0.046	-0.204	0.098	0.016	-0.079	-0.042
	[0.0196]**	[0.0167]***	[0.0085]***	[0.0088]*	[0.0086]***	[0.0088]***
KURT	0.008	-0.004	0.007	0.008	0.013	0.002
	[0.0046]*	[0.0017]***	[0.0012]***	[0.0013]***	[0.0018]***	[0.0004]***
D3M*STDEV	-3.23	0.843	-1.457	-0.359	0.529	-1.392
	[0.1817]***	[0.2559]***	[0.2883]***	[0.2155]*	[0.1675]***	[0.2671]***
D3M*SKEW	0.022	0.128	-0.108	-0.066	0.049	-0.033
	[0.0227]	[0.0279]***	[0.0107]***	[0.0114]***	[0.0106]***	[0.0121]***
D3M*KURT	-0.012	-0.015	-0.017	-0.033	0.002	-0.023
	[0.0049]**	[0.0041]***	[0.0018]***	[0.0020]***	[0.0021]	[0.0016]***
Observations:	1122	1122	1117	1121	1116	1121
Adj. Rw-squared:	0.39	0.43	0.36	0.59	0.58	0.32
Prob(F-stat)						

Note: The dependent variable is excess currency returns as defined in equation(2.2.3). Regression is the one in equation (2.4.8):

$$xr^i_{t+\tau} = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

The breakdate D1 the same as the one selected in (2.9) . We use MM-estimation. F-stats report Wald test of the null that $\gamma_{1,\tau} = \gamma_{2,\tau} = \gamma_{3,\tau} = \gamma_{4,\tau} = \gamma_{5,\tau} = \gamma_{6,\tau} = 0$. Adj. R^2_w is the gooness of fit statistic introduced in Renaud and Victoria-Fraser (2010). Huber type II standard errors are in brackets. A quick introduction to robust regression analysis is in Eviews (2013)

Table 2.8: FX EXCESS RETURNS MATCHED FREQUENCY QUANTILE REGRESSIONS

(a) AUDUSD

Eq Name:	3M_LS	3M_Q05	3M_Q10	3M_Q25	3M_Q50	3M_Q75	3M_Q90	3M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
STDEV	-0.135	-0.356	-0.423	-0.034	0.302	0.348	0.285	-0.035
	[0.2968]	[0.1242]***	[0.1363]***	[0.1237]	[0.1371]**	[0.1085]***	[0.2217]	[0.5968]
SKEW	0.158	0.048	0.058	0.049	0.071	0.232	0.431	0.47
	[0.0641]**	[0.0218]**	[0.0185]***	[0.0131]***	[0.0399]*	[0.0304]***	[0.0349]***	[0.0649]***
KURT	0.012	0.006	0.01	0.01	0.011	0.022	0.037	0.041
	[0.0129]	[0.0054]	[0.0048]**	[0.0037]***	[0.0079]	[0.0050]***	[0.0067]***	[0.0126]***
D3M*STDEV	-2.899	-2.927	-2.87	-2.795	-3.488	-3.276	-3.147	-3.004
	[0.4956]***	[0.2370]***	[0.2716]***	[0.2813]***	[0.3472]***	[0.2076]***	[0.3668]***	[0.6289]***
D3M*SKEW	-0.092	0.004	-0.001	0.011	0.019	-0.186	-0.35	-0.391
	[0.0687]	[0.0261]	[0.0253]	[0.0193]	[0.0403]	[0.0325]***	[0.0469]***	[0.0706]***
D3M*KURT	-0.017	-0.024	-0.027	-0.018	-0.011	-0.026	-0.041	-0.046
	[0.0136]	[0.0059]***	[0.0057]***	[0.0067]***	[0.0084]	[0.0050]***	[0.0073]***	[0.0129]***
Observations:	1122	1122	1122	1122	1122	1122	1122	1122
Adj. R-squared:	0.3215	0.4075	0.3364	0.2077	0.1269	0.197	0.3447	0.4409
Prob(F-stat):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Dependent variable is excess currency returns as defined in equation(2.2.3). Regression specification is: [a]

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

[a] Coefficients on intercept terms are suppressed

Table 2.8: FX EXCESS RETURNS MATCHED FREQUENCY QUANTILE REGRESSIONS

(b) EURJPY

Eq Name:	3M_LS	3M_Q05	3M_Q10	3M_Q25	3M_Q50	3M_Q75	3M_Q90	3M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
STDEV	-2.331	-1.252	-1.465	-1.81	-1.738	-1.528	-1.533	-1.317
	[0.4297]***	[0.1816]***	[0.1826]***	[0.1961]***	[0.3603]***	[0.3550]***	[0.3413]***	[0.3680]***
SKEW	-0.26	-0.17	-0.212	-0.216	-0.194	-0.144	-0.134	-0.116
	[0.0443]***	[0.0247]***	[0.0284]***	[0.0274]***	[0.0451]***	[0.0379]***	[0.0294]***	[0.0336]***
KURT	-0.006	-0.003	-0.004	-0.006	-0.003	0.016	0.027	0.04
	[0.0041]	[0.0012]***	[0.0015]***	[0.0018]***	[0.0082]	[0.0095]*	[0.0082]***	[0.0118]***
D1*STDEV	0.687	-0.292	-0.319	0.274	0.424	-0.173	-0.645	-0.979
	[0.6062]	[0.2155]	[0.2157]	[0.2604]	[0.4572]	[0.5144]	[0.4289]	[0.4071]**
D1*SKEW	0.074	0.085	0.089	0.106	0.091	-0.13	-0.365	-0.405
	[0.0752]	[0.0282]***	[0.0354]**	[0.0346]***	[0.0557]	[0.0590]**	[0.0581]***	[0.0440]***
D1*KURT	-0.028	-0.022	-0.026	-0.02	-0.022	-0.061	-0.097	-0.113
	[0.0104]***	[0.0023]***	[0.0036]***	[0.0043]***	[0.0101]**	[0.0116]***	[0.0102]***	[0.0127]***
Observations:	1122	1122	1122	1122	1122	1122	1122	1122
Adj. R-squared:	0.4294	0.2997	0.255	0.208	0.1981	0.2631	0.3867	0.4754
Prob(F-stat):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Dependent variable is excess currency returns as defined in equation(2.2.3). Regression specification is: [a]

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

[a] Coefficients on intercept terms are suppressed

Table 2.8: FX EXCESS RETURNS MATCHED FREQUENCY QUANTILE REGRESSIONS

(c) EURUSD

Eq Name:	3M_LS	3M_Q05	3M_Q10	3M_Q25	3M_Q50	3M_Q75	3M_Q90	3M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
STDEV	-0.861	-0.01	-0.008	-0.182	-0.518	-0.835	-1.519	-1.429
	[0.2385]***	[0.0956]	[0.1152]	[0.1390]	[0.1290]***	[0.1435]***	[0.2213]***	[0.1743]***
SKEW	0.125	0.046	0.045	0.059	0.098	0.123	0.178	0.183
	[0.0205]***	[0.0060]***	[0.0083]***	[0.0139]***	[0.0105]***	[0.0113]***	[0.0140]***	[0.0078]***
KURT	0.005	0.006	0.007	0.004	0.006	0.009	0.002	0.002
	[0.0026]**	[0.0008]***	[0.0008]***	[0.0013]***	[0.0018]***	[0.0016]***	[0.0022]	[0.0025]
D1*STDEV	-1.441	-1.911	-1.612	-0.797	-1.458	-1.583	-1.548	-2.233
	[0.5641]**	[0.3356]***	[0.2853]***	[0.2741]***	[0.4677]***	[0.3748]***	[0.7153]**	[0.5166]***
D1*SKEW	-0.134	-0.017	-0.03	-0.06	-0.109	-0.148	-0.209	-0.188
	[0.0241]***	[0.0081]**	[0.0085]***	[0.0155]***	[0.0148]***	[0.0188]***	[0.0337]***	[0.0242]***
D1*KURT	-0.016	-0.011	-0.013	-0.011	-0.014	-0.023	-0.018	-0.015
	[0.0037]***	[0.0018]***	[0.0016]***	[0.0023]***	[0.0032]***	[0.0032]***	[0.0046]***	[0.0040]***
Observations:	1117	1117	1117	1117	1117	1117	1117	1117
Adj. R-squared:	0.34	0.1677	0.1417	0.1236	0.1517	0.2517	0.301	0.3554
Prob(F-stat):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Dependent variable is excess currency returns as defined in equation(2.2.3). Regression specification is: [a]

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ is the θ^{th} quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted R^2 is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo R^2). Quick introduction to the quantile regression concepts are in Eviews (2013).

[a] Coefficients on intercept terms are suppressed

Table 2.8: FX EXCESS RETURNS MATCHED FREQUENCY QUANTILE REGRESSIONS

(d) GBPUSD

Eq Name:	3M_LS	3M_Q05	3M_Q10	3M_Q25	3M_Q50	3M_Q75	3M_Q90	3M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
STDEV	2.861	0.754	1.104	1.549	2.988	4.614	2.576	2.532
	[0.4514]***	[0.4192]*	[0.2254]***	[0.2440]***	[0.3011]***	[0.8388]***	[1.4936]*	[1.2621]**
SKEW	0.078	0.029	0.019	0.021	0.037	0.067	0.135	0.155
	[0.0260]***	[0.0079]***	[0.0051]***	[0.0070]***	[0.0113]***	[0.0280]**	[0.0388]***	[0.0290]***
KURT	0.007	0.005	0.004	0.007	0.009	0.009	0.007	0.006
	[0.0017]***	[0.0014]***	[0.0015]***	[0.0015]***	[0.0010]***	[0.0025]***	[0.0020]***	[0.0016]***
D1*STDEV	-1.085	1.263	1.243	0.936	-0.858	-2.729	-0.515	-0.446
	[0.5168]**	[0.6333]**	[0.2826]***	[0.2985]***	[0.3138]***	[0.8570]***	[1.5089]	[1.2730]
D1*SKEW	-0.111	-0.11	-0.102	-0.082	-0.063	-0.093	-0.114	-0.113
	[0.0329]***	[0.0139]***	[0.0091]***	[0.0150]***	[0.0169]***	[0.0298]***	[0.0436]***	[0.0420]***
D1*KURT	-0.023	-0.037	-0.037	-0.034	-0.028	-0.025	-0.016	-0.012
	[0.0039]***	[0.0029]***	[0.0025]***	[0.0035]***	[0.0021]***	[0.0037]***	[0.0034]***	[0.0027]***
Observations:	1121	1121	1121	1121	1121	1121	1121	1121
Adj. R-squared:	0.4848	0.492	0.4158	0.2655	0.2304	0.3053	0.4267	0.4817
Prob(F-stat):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Dependent variable is excess currency returns as defined in equation(2.2.3). Regression specification is: [a]

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau}D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau}stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau}skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau}kurt_t^{t+\tau} + \gamma_{4,\tau}stdev_t^{i,t+\tau} + \gamma_{5,\tau}skew_t^{i,t+\tau} + \gamma_{6,\tau}kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

[a] Coefficients on intercept terms are suppressed

Table 2.8: FX EXCESS RETURNS MATCHED FREQUENCY QUANTILE REGRESSIONS

(e) USDCAD

Eq Name:	3M_LS	3M_Q05	3M_Q10	3M_Q25	3M_Q50	3M_Q75	3M_Q90	3M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
STDEV	1.135	2.926	2.216	1.28	0.406	0.223	0.471	0.203
	[0.4719]**	[0.3510]***	[0.3330]***	[0.3680]***	[0.1767]**	[0.2310]	[0.4871]	[0.5249]
SKEW	-0.155	-0.305	-0.232	-0.163	-0.113	-0.097	-0.101	-0.098
	[0.0351]***	[0.0327]***	[0.0305]***	[0.0300]***	[0.0138]***	[0.0161]***	[0.0331]***	[0.0382]**
KURT	0.007	-0.011	0	0.012	0.011	0.009	0.007	0.005
	[0.0089]	[0.0093]	[0.0099]	[0.0074]*	[0.0032]***	[0.0032]***	[0.0059]	[0.0077]
D1*STDEV	-0.558	-2.339	-1.862	-0.805	0.07	0.536	0.659	1.28
	[0.5129]	[0.4856]***	[0.3849]***	[0.3620]**	[0.2071]	[0.2741]*	[0.4856]	[0.5567]**
D1*SKEW	0.122	0.288	0.202	0.145	0.083	0.058	0.044	0.043
	[0.0363]***	[0.0361]***	[0.0313]***	[0.0316]***	[0.0154]***	[0.0172]***	[0.0333]	[0.0388]
D1*KURT	0.008	0.027	0.016	0.003	0.004	0.005	0.008	0.016
	[0.0090]	[0.0095]***	[0.0099]*	[0.0076]	[0.0035]	[0.0033]	[0.0067]	[0.0087]*
Observations:	1116	1116	1116	1116	1116	1116	1116	1116
Adj. R-squared:	0.4806	0.4931	0.4079	0.2986	0.2795	0.3128	0.3252	0.3179
Prob(F-stat):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Dependent variable is excess currency returns as defined in equation(2.2.3). Regression specification is: [a]

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ is the θ^{th} quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted R^2 is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo R^2). Quick introduction to the quantile regression concepts are in Eviews (2013).

[a] Coefficients on intercept terms are suppressed

Table 2.8: FX EXCESS RETURNS MATCHED FREQUENCY QUANTILE REGRESSIONS

(f) USDJPY

Eq Name:	3M_LS	3M_Q05	3M_Q10	3M_Q25	3M_Q50	3M_Q75	3M_Q90	3M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
STDEV	-0.761	-0.868	-0.88	-1.164	-0.542	-0.425	-0.227	-0.248
	[0.3523]**	[0.1239]***	[0.1456]***	[0.1485]***	[0.2450]**	[0.1676]**	[0.3074]	[0.9314]
SKEW	-0.043	-0.051	-0.046	-0.032	-0.039	-0.037	-0.026	-0.028
	[0.0146]***	[0.0175]***	[0.0164]***	[0.0123]***	[0.0080]***	[0.0154]**	[0.0108]**	[0.0213]
KURT	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0
	[0.0005]***	[0.0005]***	[0.0005]***	[0.0003]***	[0.0003]***	[0.0004]***	[0.0004]	[0.0004]
D1*STDEV	-0.624	-1.482	-1.43	-1.452	-1.305	-0.371	-0.284	-0.267
	[0.5732]	[0.1953]***	[0.2533]***	[0.2143]***	[0.3960]***	[0.3148]	[0.3273]	[1.0047]
D1*SKEW	-0.015	0.028	0.021	-0.031	-0.036	-0.042	-0.072	-0.082
	[0.0232]	[0.0189]	[0.0184]	[0.0150]**	[0.0120]***	[0.0190]**	[0.0138]***	[0.0274]***
D1*KURT	-0.02	-0.009	-0.011	-0.019	-0.021	-0.02	-0.021	-0.024
	[0.0030]***	[0.0014]***	[0.0019]***	[0.0014]***	[0.0016]***	[0.0014]***	[0.0018]***	[0.0025]***
Observations:	1121	1121	1121	1121	1121	1121	1121	1121
Adj. R-squared:	0.2044	0.3042	0.2539	0.1589	0.1221	0.1429	0.1857	0.2181
Prob(F-stat):	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: Dependent variable is excess currency returns as defined in equation(2.2.3). Regression specification is: [a]

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

[a] Coefficients on intercept terms are suppressed

Table 2.9: FX EXCESS RETURNS 1M QUANTILE REGRESSIONS

(a) AUDUSD

Eq Name:	1M_LS	1M_Q05	1M_Q10	1M_Q25	1M_Q50	1M_Q75	1M_Q90	1M_Q95
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
C	0.212	0	0.071	0.205	0.198	0.236	0.428	0.432
	[0.0737]**	[0.0864]	[0.0812]	[0.1076]	[0.1360]	[0.0413]**	[0.0336]**	[0.0816]**
D1	0.053	0.268	0.136	0.023	-0.077	0.031	0.012	0.099
	[0.1249]	[0.1793]	[0.1451]	[0.1240]	[0.1439]	[0.0742]	[0.0726]	[0.1222]
STDEV	2.495	0.252	1.126	2.195	2.888	2.207	4.547	7.336
	[0.7741]**	[1.7430]	[1.1643]	[0.7458]**	[0.4163]**	[0.3880]**	[1.6435]**	[2.8579]*
SKEW	0.257	0.346	0.302	0.139	0.065	0.168	0.558	0.585
	[0.0982]**	[0.0546]**	[0.0367]**	[0.0727]	[0.0512]	[0.0945]	[0.0633]**	[0.1798]**
KURT	-0.025	0.011	-0.014	-0.065	-0.063	-0.027	0.01	0.01
	[0.0237]	[0.0346]	[0.0287]	[0.0379]	[0.0371]	[0.0150]	[0.0111]	[0.0248]
D1*STDEV	-8.825	-9.246	-8.242	-9.515	-7.672	-7.765	-11.319	-14.284
	[1.5916]**	[2.9403]**	[1.7922]**	[1.1561]**	[0.7569]**	[1.0459]**	[1.9722]**	[3.3746]**
D1*SKEW	-0.228	-0.214	-0.257	-0.077	-0.033	-0.095	-0.546	-0.74
	[0.1112]*	[0.1195]	[0.0672]**	[0.0832]	[0.0573]	[0.0987]	[0.0789]**	[0.2134]**
D1*KURT	0.016	-0.026	-0.008	0.061	0.069	0.03	-0.021	-0.042
	[0.0266]	[0.0383]	[0.0372]	[0.0385]	[0.0376]	[0.0159]	[0.0127]	[0.0270]
Observations:	1098	1098	1098	1098	1098	1098	1098	1098
R-squared:	0.2585	0.2413	0.1957	0.1447	0.1245	0.1316	0.1772	0.2141

Note: Dependent variable is excess currency returns $f_t^{t+\tau} - s_{t+\tau}$. Regression specification is:

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau}D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau}stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau}skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau}kurt_t^{t+\tau} + \gamma_{4,\tau}stdev_t^{i,t+\tau} + \gamma_{5,\tau}skew_t^{i,t+\tau} + \gamma_{6,\tau}kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ is the θ^{th} quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted R^2 is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo R^2). Quick introduction to the quantile regression concepts are in Eviews (2013).

Table 2.9: FX EXCESS RETURNS 1M QUANTILE REGRESSIONS

(b) EURJPY

Eq Name:	1M_LS	1M_Q05	1M_Q10	1M_Q25	1M_Q50	1M_Q75	1M_Q90	1M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
C	-0.065	-0.128	-0.131	-0.123	-0.095	0.02	0.044	-0.024
	[0.0427]	[0.0176]**	[0.0164]**	[0.0201]**	[0.0261]**	[0.0936]	[0.0889]	[0.1680]
D1	0.278	0.194	0.216	0.278	0.311	0.185	0.314	0.423
	[0.0695]**	[0.0682]**	[0.0424]**	[0.0413]**	[0.0372]**	[0.0976]	[0.0986]**	[0.1723]*
STDEV	-2.907	-3.247	-2.86	-2.577	-1.55	-3.933	-5.286	-2.285
	[1.0995]**	[0.6196]**	[0.5488]**	[0.6401]**	[0.5598]**	[1.0214]**	[1.3436]**	[3.5088]
SKEW	-0.07	0.049	0.039	0.005	-0.012	-0.155	-0.279	-0.096
	[0.0554]	[0.0369]	[0.0360]	[0.0375]	[0.0355]	[0.0597]**	[0.0758]**	[0.1478]
KURT	0.016	0.028	0.028	0.025	0.022	0.002	-0.005	0.032
	[0.0091]	[0.0046]**	[0.0045]**	[0.0050]**	[0.0061]**	[0.0229]	[0.0221]	[0.0332]
D1*STDEV	0.778	-0.583	-0.686	-0.718	-0.776	3.261	3.994	0.892
	[1.4537]	[0.9363]	[0.7654]	[0.9353]	[0.7291]	[1.0991]**	[1.5242]**	[3.5937]
D1*SKEW	-0.285	-0.259	-0.235	-0.154	-0.24	-0.268	-0.238	-0.553
	[0.1106]*	[0.1519]	[0.0924]*	[0.0675]*	[0.0525]**	[0.0748]**	[0.1154]*	[0.1849]*
D1*KURT	-0.085	-0.075	-0.07	-0.062	-0.077	-0.076	-0.083	-0.135
	[0.0160]**	[0.0269]**	[0.0134]**	[0.0098]**	[0.0089]**	[0.0238]**	[0.0239]**	[0.0348]*
Observations:	1100	1100	1100	1100	1100	1100	1100	1100
R-squared:	0.1929	0.1572	0.1492	0.1121	0.109	0.1389	0.2104	0.244

Note: Dependent variable is excess currency returns $f_t^{t+\tau} - s_{t+\tau}$*. Regression specification is:*

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

Table 2.9: FX EXCESS RETURNS 1M QUANTILE REGRESSIONS

(c) EURUSD

Eq Name:	1M_LS	1M_Q05	1M_Q10	1M_Q25	1M_Q50	1M_Q75	1M_Q90	1M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
C	0.213	0.118	0.097	0.013	0.023	0.2	0.298	0.374
	[0.0929]*	[0.0254]**	[0.0321]**	[0.0953]	[0.0285]	[0.0369]**	[0.0470]**	[0.0648]**
D1	-0.113	-0.243	-0.023	0.11	0.039	-0.106	-0.119	-0.109
	[0.1195]	[0.1231]*	[0.1128]	[0.1230]	[0.0480]	[0.0634]	[0.0872]	[0.1406]
STDEV	-0.579	-8.171	-6.289	-2.511	1.121	0.952	1.125	1.585
	[1.2492]	[0.8012]**	[0.9410]**	[3.3845]	[0.4103]**	[0.5043]	[0.6820]	[0.9008]
SKEW	0.304	0.196	0.201	0.149	0.171	0.295	0.31	0.367
	[0.0683]**	[0.0181]**	[0.0218]**	[0.0445]**	[0.0273]**	[0.0249]**	[0.0307]**	[0.0445]**
KURT	-0.006	0.015	0.014	0.013	0.007	0.002	-0.006	-0.011
	[0.0087]	[0.0019]**	[0.0023]**	[0.0032]**	[0.0039]	[0.0023]	[0.0024]*	[0.0027]**
D1*STDEV	0.194	9.402	3.205	-0.381	-0.658	1.263	0.718	-0.586
	[2.3791]	[5.5123]	[3.1045]	[4.0498]	[1.2037]	[1.1865]	[2.2185]	[3.5113]
D1*SKEW	-0.428	-0.25	-0.244	-0.195	-0.305	-0.488	-0.56	-0.617
	[0.0776]**	[0.0694]**	[0.0785]**	[0.0518]**	[0.0326]**	[0.0368]**	[0.0633]**	[0.0979]**
D1*KURT	-0.026	-0.048	-0.044	-0.039	-0.038	-0.043	-0.039	-0.036
	[0.0117]*	[0.0618]	[0.0194]*	[0.0321]	[0.0061]**	[0.0094]**	[0.0065]**	[0.0096]**
Observations:	1084	1084	1084	1084	1084	1084	1084	1084
R-squared:	0.192	0.1758	0.1476	0.061	0.1049	0.1665	0.2373	0.251

Note: Dependent variable is excess currency returns $f_t^{t+\tau} - s_{t+\tau}$*. Regression specification is:*

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau}D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau}stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau}skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau}kurt_t^{t+\tau} + \gamma_{4,\tau}stdev_t^{i,t+\tau} + \gamma_{5,\tau}skew_t^{i,t+\tau} + \gamma_{6,\tau}kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

Table 2.9: FX EXCESS RETURNS 1M QUANTILE REGRESSIONS

(d) GBPUSD

Eq Name:	1M_LS	1M_Q05	1M_Q10	1M_Q25	1M_Q50	1M_Q75	1M_Q90	1M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
C	-0.203	-0.283	-0.263	-0.258	-0.168	-0.226	-0.117	-0.031
	[0.0766]**	[0.0956]**	[0.0775]**	[0.0446]**	[0.0552]**	[0.0998]*	[0.1015]	[0.0921]
D1	0.166	0.232	0.16	0.168	0.125	0.252	0.197	0.15
	[0.0821]*	[0.2336]	[0.0818]	[0.0495]**	[0.0590]*	[0.1017]*	[0.1036]	[0.0955]
STDEV	9.455	5.903	6.237	6.943	6.061	10.742	12.89	15.396
	[1.5966]**	[2.4492]*	[1.9964]**	[1.0742]**	[0.9162]**	[1.2825]**	[1.0602]**	[2.8675]*
SKEW	0.141	0.009	0.022	0.053	0.115	0.221	0.323	0.312
	[0.0580]*	[0.0497]	[0.0400]	[0.0230]*	[0.0270]**	[0.0529]**	[0.0392]**	[0.0439]*
KURT	0.021	0.015	0.014	0.02	0.023	0.041	0.036	0.017
	[0.0064]**	[0.0016]**	[0.0017]**	[0.0039]**	[0.0098]*	[0.0220]	[0.0190]	[0.0139]
D1*STDEV	-6.471	-6.292	-5.446	-4.212	-2.993	-7.236	-9.449	-12.682
	[1.7175]**	[11.0621]	[2.1016]**	[1.2148]**	[1.0993]**	[1.4233]**	[1.1571]**	[2.9399]*
D1*SKEW	-0.164	-0.15	-0.029	-0.021	-0.077	-0.285	-0.351	-0.496
	[0.0836]	[0.1257]	[0.0442]	[0.0296]	[0.0459]	[0.1084]**	[0.0918]**	[0.1497]*
D1*KURT	-0.042	-0.056	-0.028	-0.037	-0.039	-0.066	-0.057	-0.048
	[0.0087]**	[0.1364]	[0.0034]**	[0.0056]**	[0.0119]**	[0.0233]**	[0.0200]**	[0.0174]*
Observations:	1100	1100	1100	1100	1100	1100	1100	1100
R-squared:	0.2828	0.1817	0.1471	0.1207	0.1028	0.1668	0.2687	0.3268

Note: Dependent variable is excess currency returns $f_t^{t+\tau} - s_{t+\tau}$. *Regression specification is:*

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

Table 2.9: FX EXCESS RETURNS 1M QUANTILE REGRESSIONS

(e) USDCAD

Eq Name:	1M_LS	1M_Q05	1M_Q10	1M_Q25	1M_Q50	1M_Q75	1M_Q90	1M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
C	-1.676	-1.003	-0.893	-2.022	-2.512	-2.439	-2.761	-2.802
	[0.3864]**	[0.2030]**	[0.2326]**	[0.2990]**	[0.3033]**	[0.3454]**	[0.5114]**	[1.4474]
D1	1.633	0.744	0.738	1.952	2.498	2.445	2.71	2.686
	[0.3878]**	[0.2071]**	[0.2346]**	[0.2998]**	[0.3036]**	[0.3457]**	[0.5125]**	[1.4478]
STDEV	18.052	13.115	11.124	17.732	23.105	23.588	25.221	26.769
	[2.5665]**	[3.3868]**	[3.5071]**	[3.1308]**	[1.7597]**	[2.0373]**	[2.6329]**	[5.2472]**
SKEW	0.324	0.246	0.215	0.453	0.494	0.416	0.472	0.416
	[0.1227]**	[0.0571]**	[0.0661]**	[0.0819]**	[0.0891]**	[0.1080]**	[0.1762]**	[0.5561]
KURT	0.358	0.194	0.178	0.451	0.551	0.528	0.607	0.607
	[0.0938]**	[0.0386]**	[0.0470]**	[0.0670]**	[0.0742]**	[0.0841]**	[0.1301]**	[0.3880]
D1*STDEV	-18.551	-13.281	-12.189	-19.524	-24.52	-23.584	-21.56	-20.103
	[2.7034]**	[3.4452]**	[3.5971]**	[3.1589]**	[1.8189]**	[2.0941]**	[2.8598]**	[5.3737]**
D1*SKEW	-0.196	-0.011	-0.06	-0.342	-0.401	-0.337	-0.418	-0.366
	[0.1275]	[0.0647]	[0.0684]	[0.0833]**	[0.0904]**	[0.1091]**	[0.1772]*	[0.5567]
D1*KURT	-0.345	-0.183	-0.166	-0.431	-0.533	-0.515	-0.601	-0.604
	[0.0941]**	[0.0387]**	[0.0472]**	[0.0671]**	[0.0742]**	[0.0842]**	[0.1301]**	[0.3880]
Observations:	1086	1086	1086	1086	1086	1086	1086	1086
R-squared:	0.1769	0.1663	0.1379	0.1134	0.1219	0.1463	0.1561	0.152

Note: Dependent variable is excess currency returns $f_t^{t+\tau} - s_{t+\tau}$*. Regression specification is:*

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau}D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau}stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau}skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau}kurt_t^{t+\tau} + \gamma_{4,\tau}stdev_t^{i,t+\tau} + \gamma_{5,\tau}skew_t^{i,t+\tau} + \gamma_{6,\tau}kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

Table 2.9: FX EXCESS RETURNS 1M QUANTILE REGRESSIONS

(f) USDJPY

Eq Name:	1M_LS	1M_Q05	1M_Q10	1M_Q25	1M_Q50	1M_Q75	1M_Q90	1M_Q95
Method:	LS	QREG	QREG	QREG	QREG	QREG	QREG	QREG
Dep. Var:	XR	XR	XR	XR	XR	XR	XR	XR
C	-0.045	-0.064	-0.069	-0.108	-0.083	-0.012	0.08	0.296
	[0.0478]	[0.0254]*	[0.0284]*	[0.0272]**	[0.0274]**	[0.0255]	[0.0591]	[0.0919]*
D1	0.429	0.225	0.51	0.565	0.598	0.453	0.179	-0.105
	[0.1040]**	[0.1331]	[0.0740]**	[0.0564]**	[0.0598]**	[0.0918]**	[0.1032]	[0.1160]
STDEV	1.188	-2.212	-1.349	0.835	2.158	1.589	1.768	1.018
	[0.7267]	[0.6556]**	[0.9340]	[0.5376]	[0.4557]**	[0.3058]**	[0.6395]**	[0.6518]
SKEW	-0.016	0.014	0.024	0.017	0.011	-0.082	-0.066	0.093
	[0.0583]	[0.0361]	[0.0418]	[0.0406]	[0.0342]	[0.0226]**	[0.0665]	[0.0809]
KURT	0.005	0.006	0.006	0.008	0.007	0	-0.003	-0.006
	[0.0023]	[0.0011]**	[0.0015]**	[0.0016]**	[0.0018]**	[0.0014]	[0.0012]**	[0.0009]*
D1*STDEV	-7.753	-4.328	-9.908	-8.67	-9.08	-6.38	-3.504	0.209
	[1.8324]**	[2.8240]	[1.5403]**	[1.0106]**	[0.8561]**	[1.0047]**	[2.3640]	[1.9650]
D1*SKEW	-0.062	-0.028	-0.252	-0.103	-0.066	0.061	0.058	0.006
	[0.0717]	[0.1558]	[0.0767]**	[0.0488]*	[0.0400]	[0.0348]	[0.0859]	[0.0929]
D1*KURT	-0.04	-0.022	-0.056	-0.06	-0.066	-0.046	-0.013	-0.002
	[0.0117]**	[0.0186]	[0.0098]**	[0.0064]**	[0.0074]**	[0.0144]**	[0.0053]*	[0.0042]
Observations:	1098	1098	1098	1098	1098	1098	1098	1098
R-squared:	0.1158	0.1884	0.1172	0.0878	0.0776	0.0678	0.0764	0.0961

Note: Dependent variable is excess currency returns $f_t^{t+\tau} - s_{t+\tau}$*. Regression specification is:*

$$Q^{xr^i_{t+\tau}}(\theta|.) = \gamma_{0,\tau} + \gamma_{00,\tau} D1^{i,\tau} + D1^{i,\tau} * \gamma_{1,\tau} stdev_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{2,\tau} skew_t^{i,t+\tau} + D1^{i,\tau} * \gamma_{3,\tau} kurt_t^{t+\tau} + \gamma_{4,\tau} stdev_t^{i,t+\tau} + \gamma_{5,\tau} skew_t^{i,t+\tau} + \gamma_{6,\tau} kurt_t^{i,t+\tau} + \epsilon_{i,t+\tau}.$$

$Q^{xr^i_{t+\tau}}(\theta|.)$ *is the* θ^{th} *quantile of excess currency returns conditional on the regressors. Bootstrap standard errors are in brackets. Adjusted* R^2 *is adjusted version of the Koenker and Machado (1999) goodness of fit measure for quantile regressions(Adjusted pseudo* R^2*). Quick introduction to the quantile regression concepts are in Eviews (2013).*

Chapter 3

DENSITY FORECAST EVALUATION-BASED TESTS OF UNCOVERED INTEREST PARITY

3.1 Introduction

The simple risk-neutral efficient market hypothesis predicts that the expected gain from holding one currency instead of another must be exactly offset by the two countries' nominal interest rate differential.[1] This condition, known as uncovered interest parity (UIP), is the most common way of testing for FX market efficiency and can be expressed as follows:

$$\Delta_{\tau} s^{e}_{t+\tau} = i_t - i^{*}_t. \tag{3.1.1}$$

In equation (3.1.1), s_t is the logarithm of the spot exchange rate[2] while i_t and i^{*}_t are the domestic and foreign risk-free nominal interest rates respectively. If I further assume that the no-arbitrage condition of covered interest parity (CIP), which can be approximated by the following equation:

$$f^{t+\tau}_t - s_t = i_t - i^{*}_t \tag{3.1.2}$$

holds [3], then the UIP condition in equation (3.1.1) can also be written as follows:

$$\Delta_{\tau} s^{e}_{t+\tau} = f^{t+\tau}_t - s_t. \tag{3.1.3}$$

Equation (3.1.3) implies that if market participants are risk-neutral and have rational expectations, then the forward rate is an unbiased predictor of the future spot rate. Empirical

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[1] The interest rate differential represents the opportunity cost of holding funds in one currency rather than another.

[2] I define exchange rate as the domestic price of foreign currency.Therefore, if s_t goes up, it means the domestic currency has depreciated.

[3] The CIP condition has generally be found to be empirically valid

tests of the UIP condition usually take the form of the following linear regression:

$$(s_{t+\tau} - s_t) = \alpha + \beta(f_t^{t+\tau} - s_t) + \epsilon_{t+\tau}, \tag{3.1.4}$$

Testing the UIP using equation regression (3.1.4) is done by testing the null hypothesis that $\alpha = 0$ and $\beta = 1$. Empirical estimations of equation (3.1.4) above consistently yield estimates of β that are closer to -1 than to 1, and such regressions are unable to explain variation of exchange rate changes[4]. This perennial failure of the UIP condition is commonly known as the uncovered interest parity(UIP) puzzle or the forward premium puzzle. It suggests that the forward premium, $f_t^{t+\tau} - s_t$, contains little information about the future dynamics of the spot exchange rate.

The UIP puzzle is usually attributed to time-varying risk premia and market expectation biases. Sarno and Taylor (2002) argue that a major problem with much of the empirical literature on explaining the rejection of the simple risk neutral efficient market hypothesis is that in testing one leg of the joint hypothesis, researchers tend to assume that the other leg to be true. For example, on one hand, researchers who pursue risk premia explanations such as Fama (1984) and Hodrick and Srivastava (1984) assume that market participants have rational expectations. On the other hand, Bilson (1981) and Cumby and Obstfeld (1984) assume risk-neutrality and thus interpret deviations from biased-ness of the forward exchange rate as suggesting rejection of the rational expectations hypothesis. Furthermore, regression-based tests such as the Fama (1984) regressions, impose restrictive distributional assumptions which make it hard to pin down either of the two potential causes. Third, there are small sample problems frequently mentioned in the literature as potential reasons for the UIP puzzle, for example, learning hypothesis (Lewis (1989)), peso problem (Krasker (1980)) and regime changes (Evans and Lewis (1995)).

Understanding the reasons for empirical failure of the UIP is crucial because the UIP condition is a cornerstone of many international macroeconomic models, in which it is usually taken as given. In this paper, I argue that standard OLS-based tests based on regression equation (3.1.4) may be misleading because of the auxiliary assumptions inherent

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[4] Clarida and Taylor (1997), for example, report $R^2 s$ ranging from 0.00 to 0.04 .

in running the OLS regressions. I then propose an options-based approach that exploits the relationship between options-implied risk-neutral densities and physical densities. This relationship is given in equation (3.2.16). Using this options-based approach, I do not reject the null hypothesis that option-implied risk-neutral densities accurately forecast physical densities of future exchange rates. The density forecast evaluation is a stronger test of the UIP than the regression-based tests based on equation (3.1.4). The analysis in this paper suggests that care should be taken in disentangling rejections of the UIP condition from rejections of the auxiliary assumptions inherent in standard tests of the hypothesis.

The density forecast evaluation approach does not require us to make distributional assumptions about $s_{t+\tau}$ or assumptions about market participants' expectation formation mechanisms.

3.2 Theoretical Background and Empirical Methodology

3.2.1 Structural Derivation of UIP Condition

Consider the problem faced by an investor who allocates her portfolio among risky assets with the goal of maximizing the expected utility of next period wealth. In each period, the investor has n risky assets to choose from. The vector of gross returns is therefore given by $r_{t+1} = (r_{1,t+1}, ..., r_{n,t+1})$. If we arbitrarily set W_t to 1, then $W_{t+1} = \alpha_t^{'} r_{t+1}$, where α is an n by 1 vector of portfolio weights.

The above investors problem is to choose α_t to maximize her next period expected utility:

$$\begin{aligned} \mathbb{E}_t[U(W_{t+1})] &= \mathbb{E}_t[U(\alpha_t^{'} r_{t+1})] \\ &= \int ... \int U(W_{t+1}) f(r_{t+1}) dr_{1,t+1} dr_{2,t+1} ... dr_{n,t+1} \end{aligned} \tag{3.2.1}$$

subject to the condition that $\sum_{i=1}^{n} \alpha_{i,t} = 1$, where $f(r_{t+1})$ is the joint probability distribution of r_{t+1}.

CARA and Normality reduce problem to mean-variance optimization

Let us further assume that the investor has constant absolute risk aversion (CARA) utility and that returns are conditionally normally distributed. The CARA utility assumption means the utility is given by

$U(W_{t+1}) = -e^{-\gamma W_{t+1}}$, where $\gamma \geq 0$ is the coefficient of absolute risk aversion. The distributional assumption $r_{t+1} \sim N(\mu_{t+1}, \Sigma_{t+1})$ implies that $W_{t+1} \sim N(\mu_{p,t+1}, \sigma^2_{p,t+1})$, where $\mu_{p,t+1} = \alpha'_t \mu_{t+1}$ and $\sigma^2_{p,t+1} = \alpha'_t \Sigma_{t+1} \alpha_t$

With the above two assumptions, expression (3.2.1) reduces to[5]

$$\mathbb{E}_t[U(W_{t+1})] = -\mathbb{E}_t[e^{-\gamma W_{t+1}}] = \gamma \mu_{p,t+1} - \frac{1}{2}\gamma^2 \sigma^2_{p,t+1} \tag{3.2.2}$$

Equation (3.2.2) demonstrates that under the assumptions of CARA utility function and conditional normality of returns, the general portfolio allocation problem (3.2.1) reduces to the mean-variance optimization problem.

If I further assume that our investor has a 2-asset portfolio made up of a nominally safe domestic bond and a foreign bond, and that she allocates a fraction α of her wealth to the domestic bond, then next period wealth expressed in local currency units is given by

$$W_{t+1} = \left[\alpha(1 + i_t) + (1 - \alpha)(1 + i^*_t)\frac{S_{t+1}}{S_t.}\right] W_t \tag{3.2.3}$$

In this 2-asset example and CARA utility and conditionally normal returns the expressions for the conditional mean and variance of next period wealth are given by:

$$\begin{aligned} \mu_{p,t+1} &= \left[\alpha(1 + i_t) + (1 - \alpha)(1 + i^*_t)\tfrac{\mathbb{E}_t S_{t+1}}{S_t}\right] W_t, \\ \sigma^2_{p,t+1} &= \tfrac{(1-\alpha)^2(1+i^*_t)^2 Var_t(S_{t+1}) W_t^2}{S_t^2} \end{aligned} \tag{3.2.4}$$

Plugging the expressions in equation (3.2.4) into objective function (3.2.2), taking the first order condition with respect to α and rearranging the first order condition yields the following equation which implicitly determines the optimal α:

$$(1 + i_t) - (1 + i^*_t)\frac{\mathbb{E}_t S_{t+1}}{S_t} = \frac{-\gamma W_t (1 - \alpha)(1 + i^*_t)^2 Var_t(S_{t+1})}{S_t^2}. \tag{3.2.5}$$

Equation (3.2.5) reduces to the UIP condition if we assume that all investors are risk-neutral

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[5]The second equality follows from the fact that $e^{-\gamma W_{t+1}} \sim LN(-\gamma\mu_{p,t+1}, \gamma^2\sigma^2_{p,t+1})$, so $\mathbb{E}_t[e^{-\gamma W_{t+1}}] = -\gamma\mu_{p,t+1} + \gamma^2\sigma^2_{p,t+1}$

($\gamma = 0$):[6]

$$\frac{1+i_t}{1+i_t^*} = \frac{\mathbb{E}_t S_{t+1}}{S_t}. \tag{3.2.6}$$

The Fama regression in equation (3.1.4) tests a logarithmic version of equation (3.2.6). The key steps in deriving the testable restrictions in equation (3.2.6) are the joint assumptions of CARA utility and conditional normality of next period wealth, which reduce the investor's optimization to mean-variance.

3.2.2 Risk-neutral pricing version of the UIP Hypothesis[7]

Under the UIP hypothesis, if agents are risk-neutral and act rationally, then the expected change in the spot rate compensates for the interest rate differences between two countries:

$$\frac{\mathbb{E}_t^P(S_{t+\tau})}{S_t} = e^{(i_t^\tau - i_t^{*,\tau})}. \tag{3.2.7}$$

In equation (3.2.7),the left hand side is the expected exchange rate change, while the right hand side is the continuously compounded interest rates at time to maturity τ. $\mathbb{E}_t^P(.)$ denotes rational expectations based on information available at time t. I will denote the actual distribution over which the expectation in equation (3.2.7) is taken by $\pi_t^P(.)$.

Under the covered interest parity condition (which tends to be empirically valid) , the forward exchange rate and the current spot rate are related by the following equation:

$$\frac{F_t^{t+\tau}}{S_t} = \frac{\mathbb{E}_t^P(S_{t+\tau})}{S_t}. \tag{3.2.8}$$

From equations (3.2.7) and (3.2.8), I see that the UIP condition combined with CIP is equivalent to the hypothesis that the forward exchange rate is an unbiased predictor of future spot exchange rate:

$$\mathbb{E}_t^P(S_{t+\tau}) = F_t^{t+\tau}. \tag{3.2.9}$$

The forward unbiasedness hypothesis in equation (3.2.9) is the version of the UIP hypothesis

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[6]UIP will also hold if $\alpha = 1$, regardless of investors' degree of risk Aversion.

[7]also see Cincibuch and Vavra (2004)

that is usually tested in empirical studies.

To derive a risk-neutral pricing version of the UIP, I note that in the absence of arbitrage, the price of a security can be expressed as the discounted expected value of the security's pay-off, where the expectation taken with respect to the appropriate risk-neutral measure. For example, the time t price of a European-style call option with strike price K and tenor τ is given by

$$C(S_t, K, \tau) = e^{-i_t^{\tau}\tau}\mathbb{E}_t^Q(S_{t+\tau} - K). \tag{3.2.10}$$

The pricing equation (3.2.10), I see that the price of a European-style call option with a strike price of zero is therefore

$$C(S_t, 0, \tau) = e^{-i_t^{\tau}\tau}\mathbb{E}_t^Q(S_{t+\tau}). \tag{3.2.11}$$

Under the assumption of no arbitrage , a call option price with a strike price of zero should have a price of

$$C(S_t, 0, \tau) = S_t e^{-i_t^{*,\tau}\tau}. \tag{3.2.12}$$

Equations (3.2.11) and (3.2.12) imply that, under no arbitrage, the following equality holds:

$$\mathbb{E}_t^Q(S_{t+\tau}) = S_t e^{(i_t^{\tau} - i_t^{*,\tau})\tau} \tag{3.2.13}$$

Finally, combining (3.2.13) and (3.2.7), I see that the UIP condition under CIP can be expressed as

$$\mathbb{E}_t^Q(S_{t+\tau}) = \mathbb{E}_t^P(S_{t+\tau}) \tag{3.2.14}$$

Expression (3.2.14), which is concerned about equality of first moments, can be generalized to equality of whole densities:

$$\pi_t^Q(S_{t+\tau}) = \pi^P(S_{t+\tau}). \tag{3.2.15}$$

Thus, one way of testing the UIP hypothesis is to test for the equality of the first moments of the risk neutral density and the first moment of the physical distribution of future exchange rate distributions. Infact, I can obtain a generalized version of the UIP hypothesis

Density forecasting and the risk-premia explanation of the UIP

As pointed out in Jackwerth (2000), in each state of the world, the following relationship exists between market-wide risk-neutral and subjective distributions and risk aversion functions across wealth:

$$risk{-}neutral\ probability\ =\ subjective\ probability\ X\ risk\ aversion\ adjustment \quad (3.2.16)$$

The relationship in equation (3.2.16) allows us to pin down the forecasting accuracy of option-implied risk-neutral distributions for the physical distributions to time-varying risk premia. Furthermore, since I do not make assumptions regarding market participants' expectation formation mechanisms when extracting risk-neutral densities, I am able to focus on testing the time-varying risk premia leg of the UIP hypothesis without having to assume that the rational expectations leg is satisfied.

Under some commonly used utility functional forms such as power utility or CRRA, the risk-neutral density and the physical density only differ in first moments, such that the hypotheses tested in their first moments. In such cases, the hypotheses being tested in expressions (3.2.14) and (3.2.15) are equivalent.

3.3 Data and Empirical Strategy

3.3.1 Data Description and o-t-c Market Conventions

In the over-the-counter FX options market, exchange rates are quoted as domestic price of foreign currency. However, "foreign" or "domestic" have no geographic significance, but according to pre-existing market quoting conventions. Table (3.1A) gives examples of the FX market quoting conventions for some selected currency pairs . For example, AUDUSD refers to units of USD per AUD.

[INSERT TABLE (3.1) HERE]

Our data are o-t-c 1 month currency options for the five currency pairs listed in table (3.1A) covering the period May 2003 to December 2011. I start with 1 month observed at a daily frequency and create non-overlapping data sets for each currency pair.

Using o-t-c FX option price data for the density forecast evaluation exercise has several advantages. First, new options with one month maturity are issued daily, so that it is possible to have time series of 1m option prices. Second,most currency options traded in the o-t-c market are European-style. Since European-style options can only be exercised at maturity, by using over-the counter data, I avoid the complications that come with having to adjust for the possibility of early exercise. Lastly, FX options traded is concentrated in the o-t-c market, so prices in the market are more likely to better to capture market sentiments than those in thinly traded exchange market.

As can be seen from table (3.1C), o-t-c FX option prices are quoted in terms of implied volatility from the Black-Scholes option pricing formula. The use of the Black-Scholes formula and terminology does not,however, mean the prices ere obtained using the Black-Scholes model. There is a 1-1 relationship between the volatility parameter and the call option price in the Black-Scholes call pricing formula, so option prices can be quoted either in terms of currency units or in terms of implied volatility.

Another o-t-c currency option market convention is the use of the option δ rather than the exercise price as a measure of the moneyness of an option. The δ of an option is the rate of change of the price of option with respect to change in the price of the underlying asset ($\delta = \frac{\partial C}{\partial S}$).

Finally, in the o-t-c market, currency options are traded in combinations, with the most actively traded being at-the-money straddles, 25δ strangles and 25δ risk reversals. These combinations are defined as follows:

$$\begin{aligned} atm_t &= \sigma_{call}(0.5) \\ rr_t &= \sigma_{call}(0.25) - \sigma_{put}(0.25) = \sigma_{call}(0.25) - \sigma_{call}(0.75) \\ vwb_t &= \frac{\sigma_{call}(0.25)+\sigma_{put}(0.25)}{2} - \sigma_{call}(0.50) \end{aligned} \tag{3.3.1}$$

Rearranging the above equations give the following formulae for the three implied volatilities of plain vanilla options, at deltas 0.25, 0.50 and 0.75 :

$$\begin{aligned} \sigma_{call}(0.25) &= vwb_t + atm_t + \tfrac{rr_t}{2} \\ \sigma_{call}(0.50) &= atm_t \\ \sigma_{put}(0.25) &= vwb_t + atm_t - \tfrac{rr_t}{2} \end{aligned} \tag{3.3.2}$$

From the three traded combinations, I recover three points on the volatility smile. At this point, the volatility smile is in the $(\sigma - \delta)$ space used in the market. The next section describes a methodology to both convert the smile into (C-K) space and also get a continuum of strike prices from the three observed points.

Our options data consists of option prices for 25δ RR, 25δVWB and *atm* straddles, covering the period 1 May 2003 to December 2011, and were obtained from a major FX options trader. Plots of the non-overlapping data sets created from the data sets for the first trading day of each month are shown in figure (3.1).

3.3.2 Extracting Risk-Neutral Densities: The Malz (1997) Method

For a given currency pair and tenor, I extract a time series of option-implied risk neutral densities of future spot rate using the"volatility smile function" method described in Malz (1997). The Malz (1997) method builds on a result by Breeden and Litzenberger (1978), who show that the option-implied probability density of future spot rates can be extracted from a set of European-style option price with a continuum of exercise prices. In particular, under the risk-neutral probability measure, the price of a European-style call option is the expected value of its pay-off at maturity, discounted at the risk-free rate:

$$C(t,T,K) = e^{r^d \tau} \int_0^\infty max(S_T - K, 0)\pi_t^Q(S_T)dS_T = e^{r^d \tau} \int_K^\infty (S_T - K)\pi_t^Q(S_T)dS_T. \tag{3.3.3}$$

Taking the partial derivative of C with respect to the exercise price yields:

$$\frac{\partial C(t,T,K)}{\partial K} = e^{r^d \tau}(1 - \Pi_t^Q(S_T)), \tag{3.3.4}$$

where $\pi_t^Q(S_T)$ is the risk-neutral cumulative probability density of future spot rates. The probability density function of future spot rate can be obtained by differentiating equation (3.3.4) and rearranging:

$$\frac{\partial^2 C(t,T,K)}{\partial K^2} = e^{-r^d\tau}\pi_t^Q(S_T),$$

which yields

$$\pi_t^Q(S_T) = e^{r^d\tau}\frac{\partial^2 C(t,T,K)}{\partial K^2} \tag{3.3.5}$$

The Breeden-Litzenberger relationship in equation (3.3.5) requires a continuum of strike prices, while in the currency options market I only observe a discrete number of strike prices. Another issue is that currency option prices are quoted in terms of implied volatility and moneyness is quoted in terms of option delta. To use the Breeden and Litzenberger (1978) result in practice, I therefore need a way to obtain the price of a call option with an arbitrary exercise price, and then convert the volatility smile from the $(\delta_{call} - \sigma)$ space in which currency options are traded to the $(K - C)$ space where the Breeden and Litzenberger (1978) result can be exploited to estimate $\pi_t^*(S_T)$. Malz (1997) posits a continuous volatility smile function constructed by interpolating a quadratic functional form through the observed prices of option combinations. He assumes the specification:

$$\hat{\sigma_\delta}(\delta_{call}) = b_0 atm_t + b_1 rr_t(\delta_{call} - 0.50) + b_2 vwb_t(\delta_{call} - 0.50)^2 \tag{3.3.6}$$

Malz (1997) then chooses parameters b_0,b_1 and b_2 such that atm_t, rr_t and vwb_t are on the fitted volatility smile on a given day. This requires that $b_0 = 1$, $b = 16$ $b_2 = -2$. [8] The next step is to convert the volatility smile from $(\sigma - \delta)$ to $(C - K)$ space. I use the Black-Scholes formula. It is worth stressing again that use of the Black-Scholes formula here does not imply the Malz (1997) method assumes any of the assumptions underlying the Black-Scholes model. I can plug the expression for the delta of a call option into equation (3.3.6), to get:

$$\hat{\sigma_\delta}(\delta_{call}) = b_0 atm_t + b_1 rr_t(e^{-r^f\tau}\Phi(d_2) - 0.50) + b_2 vwb_t(e^{-r^f\tau}\Phi(d_1) - 0.50)^2 \tag{3.3.7}$$

[8] derived in appendix (.2.1)

Finally, the formula for the price of a European call option with strike price K is given by:

$$C(t, K, T,) = e^{-r^f \tau} S_t \Phi \left(\frac{ln\left[\frac{S}{K}\right] + (r^d - r^f + \frac{\sigma^2}{2})\tau}{\sigma\sqrt{\tau}} \right) - e^{-r^f \tau} K \Phi \left(\frac{ln\left[\frac{S}{K}\right] + (r^d - r^f - \frac{\sigma^2}{2})\tau}{\sigma\sqrt{\tau}} \right) \tag{3.3.8}$$

To get the volatility smile into the $(K - C)$ space the two equations (3.3.7) and (3.3.8) above have to be solved simultaneously using numerical methods. Once the volatility smile is in the $(K - C)$ space, I exploit the Breeden and Litzenberger (1978) result and estimate risk neutral density on a given day by differencing the volatility smile twice. A graphical illustration of results from the four stages of the Malz (1997) method are is shown in figure (3.2).

Castagna (2010) suggests that any framework for fitting the volatility smile from a few number of observed strike prices be judged on the following categories: parsimony, consistency and intuitiveness. Although the Malz (1997) methodology lacks a solid financial justification, it is attractive because it is parsimonious: it uses only three observed option prices to estimate the entire volatility smile. Additionally, the methodology does not require specification of a stochastic process followed by the underlying spot exchange rate. This is an attractive property because it means the methodology can be applied even when the exchange rate regime cannot be identified with certainty or where the degree of government influence is unclear. The quadratic specification in equation (3.3.6) is intuitive as it captures the information about the smile expressed by each of the option combinations. The straddle volatility captures the general level of implied volatility, the 25δ VWB captures the curvature of the volatility smile, and the 25δ RR captures the slope of the smile.

3.3.3 Density Forecast Evaluation

I use the density forecast evaluation framework introduced in (Diebold et al. (1998)). These authors show that it is possible to pin down a relationship between the true data generating process and the time series of estimated density forecasts through the probability integral transform of realized spot rates with respect to the density forecasts. Let $S_T$be the realization of the spot exchange rate at maturity. Then, u_t, the probability integral transform (PIT) of S_T is given by the expression:

$$u_t(S_T) = \int_{-\infty}^{S_T} \hat{\pi}_t^Q(u)du \equiv \hat{\Pi}_t^Q(S_T) = PIT(S_T) \tag{3.3.9}$$

That is, $u_t(S_T)$ is the probability, using the estimated RND, of observing a spot rate at maturity that is less than S_T. Diebold et al. (1998) show that if the estimated density has the same predictive ability as the true density, then it should not be able to predict the probability that, at maturity, the spot rate will be less than S_T. Under the same hypothesis, the time series of $u_t(S_T)$ should be independent and identically distributed observations from the uniform (0, 1) distribution. Using the inverse transform theorem, I get that under the same null hypothesis, the series

$$z_t = \Phi^{-1}(u_t) = \Phi^{-1}\left(\hat{\pi}_t^Q(u)du\right) \sim i.i.d.N(0,1) \tag{3.3.10}$$

where Φ is the standard normal cumulative distribution function (cdf). Berkowitz (2001) recommends working with the z_t series instead of the u_t series because the normal distribution is generally easier to work with the normal distribution

Separate Tests of Normality and Independence

I use the Jarque-Bera and the D'agostino tests to test for normality of the z_t series. The D'augostino normality test is particularly insightful since it tells us whether the rejection of the null is coming from skewness or from excess kurtosis. This finding is in contrast with commonly used utility functions in macro models of exchange rates that imply that physical densities and risk neutral densities only differ in first moments. To test for this independence, I carry out Ljung-Box autocorrelation tests for powers of z_t series.

$$\{(z_{t+1|t} - z_{t+1|t})\}^k\}_{t=1}^{20}, k = 1, 2, 3, 4. \tag{3.3.11}$$

Berkowitz (2001) Likelihood Ration Joint Test of Normality and Independence

A potential weakness of the above density forecast evaluation tests is that the standard normality and independence tests for the probability integral transforms are carried separately. A joint test of independence and normality of the z_t would increase the power of the test. Berkowitz (2001) suggests a likelihood-ratio joint test for normality and independence of the z_t . Berkowitz (2001) reduces the test for the standard normality to the test that the z_t series has zero mean and unit variance. He posits an AR (1) model for z_t:

$$z_t - \mu = \rho(z_{t-1} - \mu) + \epsilon_t, \epsilon_t \sim N(0, \sigma^2). \tag{3.3.12}$$

The joint null hypothesis that the z_t series is independent, has unit variance and has zero mean is equivalent to imposing the following restrictions on the AR(1) in equation (16):$\mu = 0$,$\rho = 0$, and $\sigma^2 = 1$. The alternative hypothesis is that z_t follows an alternative Gaussian AR(1) process. The log-likelihood function for this AR(1) model is given by the following expression:

$$l(\mu, \sigma^2, \rho) = -\frac{1}{2}log(2\pi) - \frac{1}{2}log\left(\frac{\sigma^2}{1-\rho}\right) - \frac{z_1 - \frac{\mu}{1-\rho}}{\frac{2\sigma^2}{1-\rho}} - \frac{n-1}{2}log(4\pi\sigma^2) - \sum_{t=2}^{T}\left[\frac{z_t - \mu(1-\rho) - \rho(z_{t-1})}{2\sigma^2}\right]. \tag{3.3.13}$$

Under the joint null hypothesis, the log-likelihood reduces to:

$$l(0,1,0) = -\frac{n}{2}log(2\pi) - \frac{n-1}{2}log(2) - \sum_{t=1}^{n} z_t. \tag{3.3.14}$$

The likelihood ratio test statistic for this joint test is therefore given by the expression:

$$LR = -2(l(0,1,0) - l(\hat{\mu}, \hat{\sigma^2}, \hat{\rho})) = -2\left[-\frac{n}{2} - log(2\pi) - \frac{n-1}{2}log(2) - \sum_{t=1}^{n} z_t - l(\hat{\mu}, \hat{\sigma^2}, \hat{\rho}\right] \sim \chi^2(3). \tag{3.3.15}$$

3.4 Discussion of Empirical Results

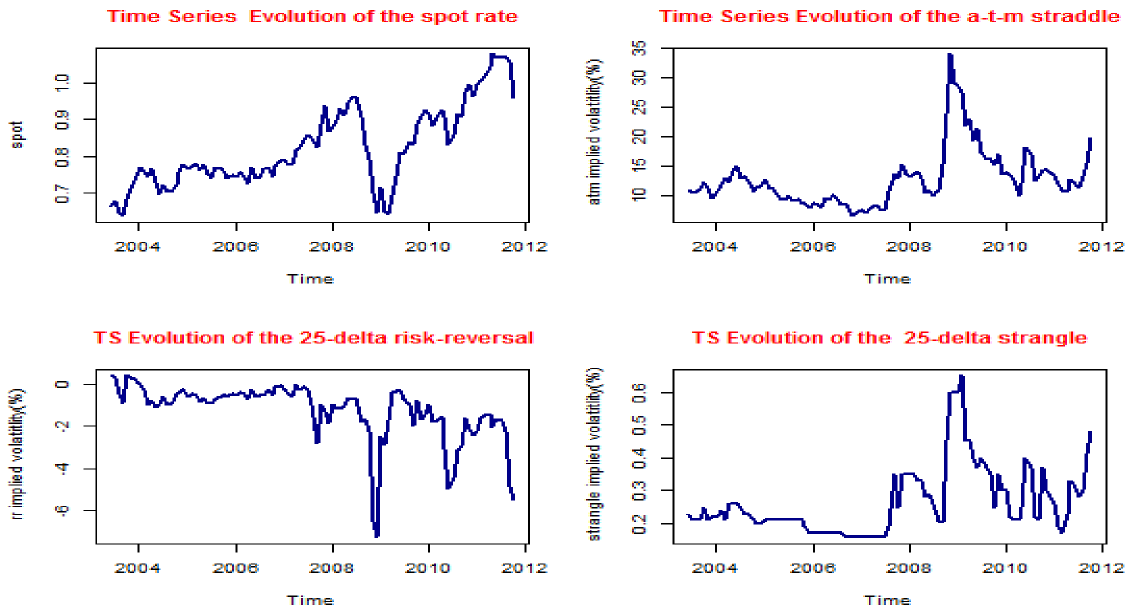
For all currency pairs, the null hypotheses of i.i.d series is not rejected. The results also show that the null hypothesis of normality cannot be rejected for all z_t series. In carrying out the Ljung-Box tests, I specify the number of lags to be tested for autocorrelation to 20. However, the results do not depend on the number of lags ; as shown in the plots of Ljung-Box p-values against number of lags shown in bottom right diagrams in of the panel of diagrams in figures 3.3(a) to 3.3(e).

The panel of diagrams in figures 3.3(a) to 3.3(e) show further insights on the density forecasting performance of option-implied distributions. If the forecasting model is correctly specified, the PIT series should be distributed i.i.d $U(0, 1)$, and the histograms of the PIT series for each currency pair and tenor would be flat.

The analysis in this paper suggests that rejections of the UIP may be due to overly restrictive auxiliary assumptions imposed in standard testing methods. This paper uses FX option prices and a density forecast evaluation framework to revisit tests of the UIP hypothesis, and argue that perennial failure of this foreign exchange efficiency market hypothesis is most likely due to overly restrictive auxiliary assumptions in the conventional Fama regression method for testing the hypothesis. Using a density forecast evaluation framework to side-step the regression-based testing approach, I am unable to reject the UIP hypothesis for five major currency pairs. My findings suggest that the documented perennial empirical failure of the UIP hypothesis may be due to overly restrictive additional assumptions embedded in the Fama regressions testing framework.

Figure 3.1: Time Series Plots of FX Traded Options

(a) AUDUSD 1M



(b) EURUSD 1M

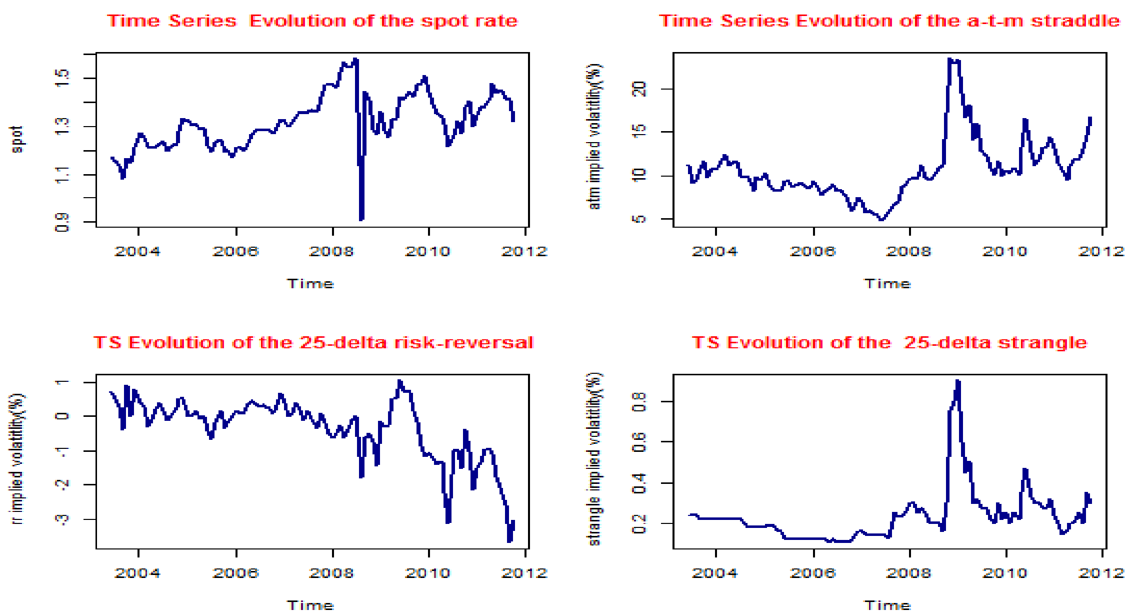
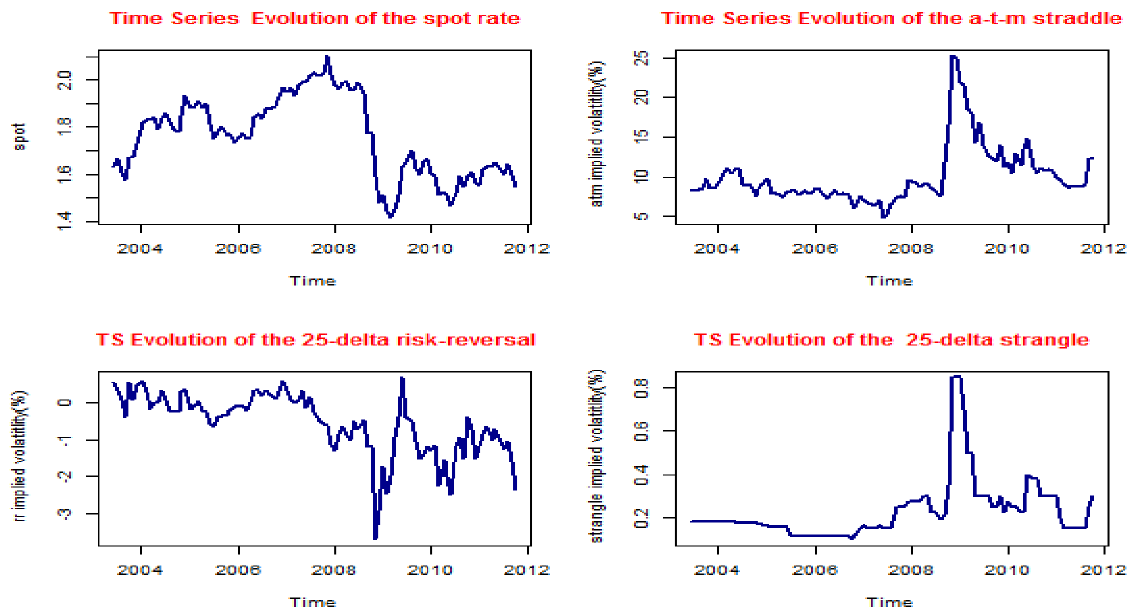


Figure 3.1: Time Series Plots of FX Traded Options

(c) GBPUSD 1M



(d) USDCAD 1M

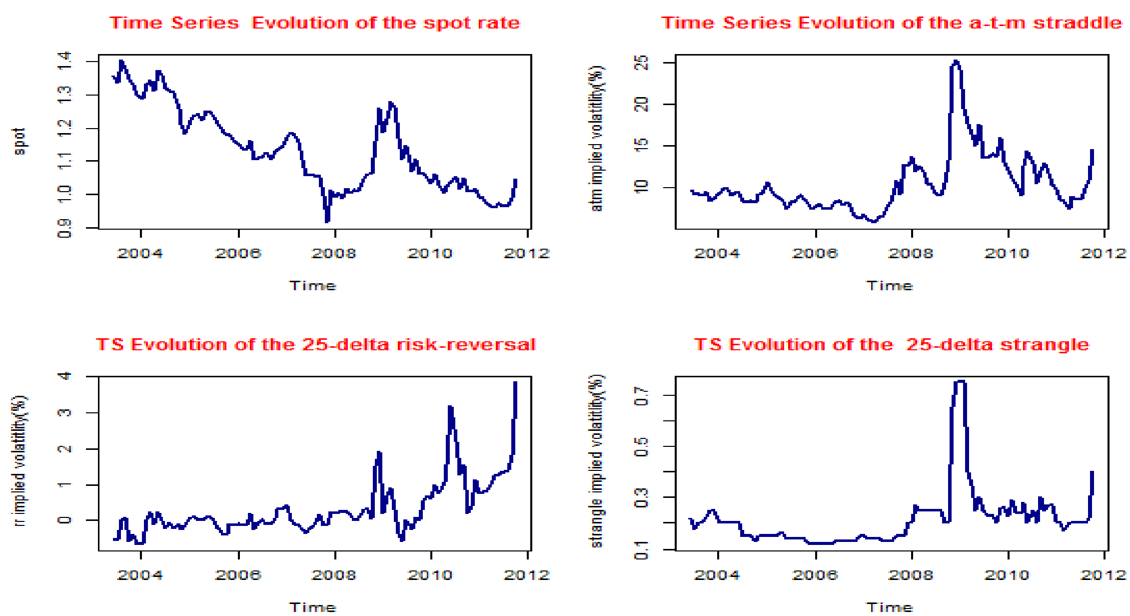


Figure 3.1: Time Series Plots of FX Traded Options

(e) USDJPY 1M

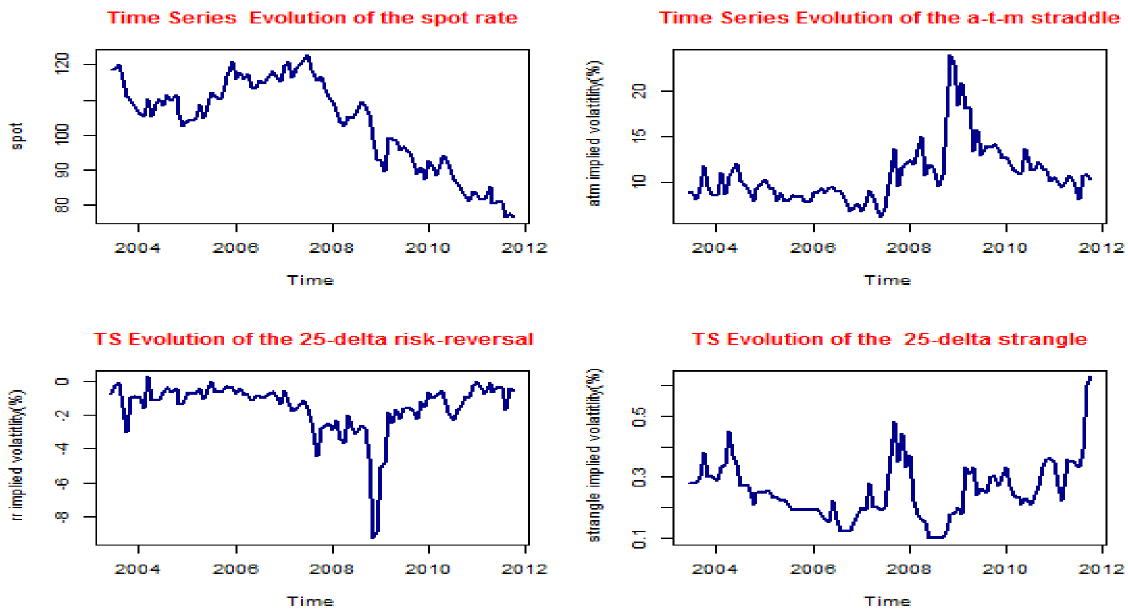


Figure 3.2: Time Series Plots of FX Traded Options

(a) Malz Method Stages

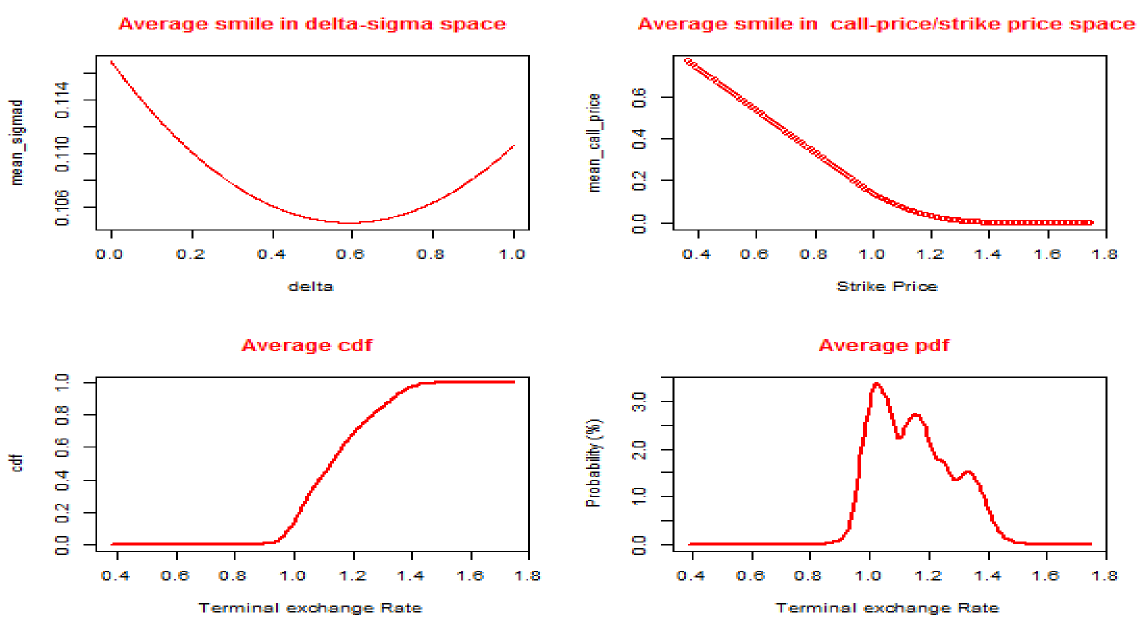
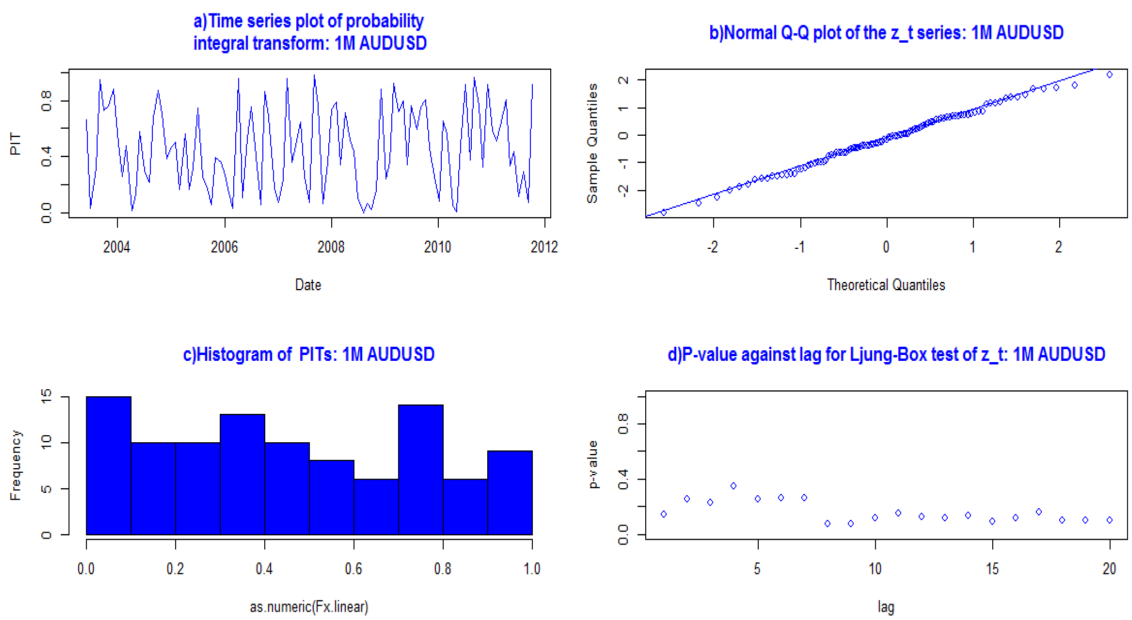


Figure 3.3: Empirical Properties of Extracted Probability Integral Transforms

(a) AUDUSD 1M



(b) EURUSD 1M

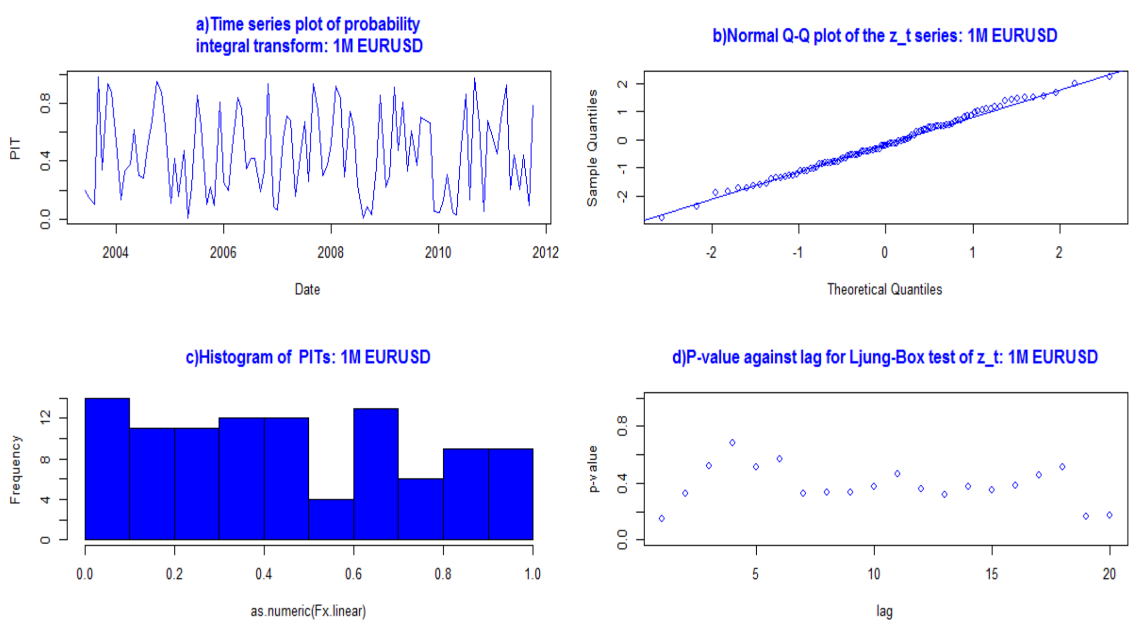
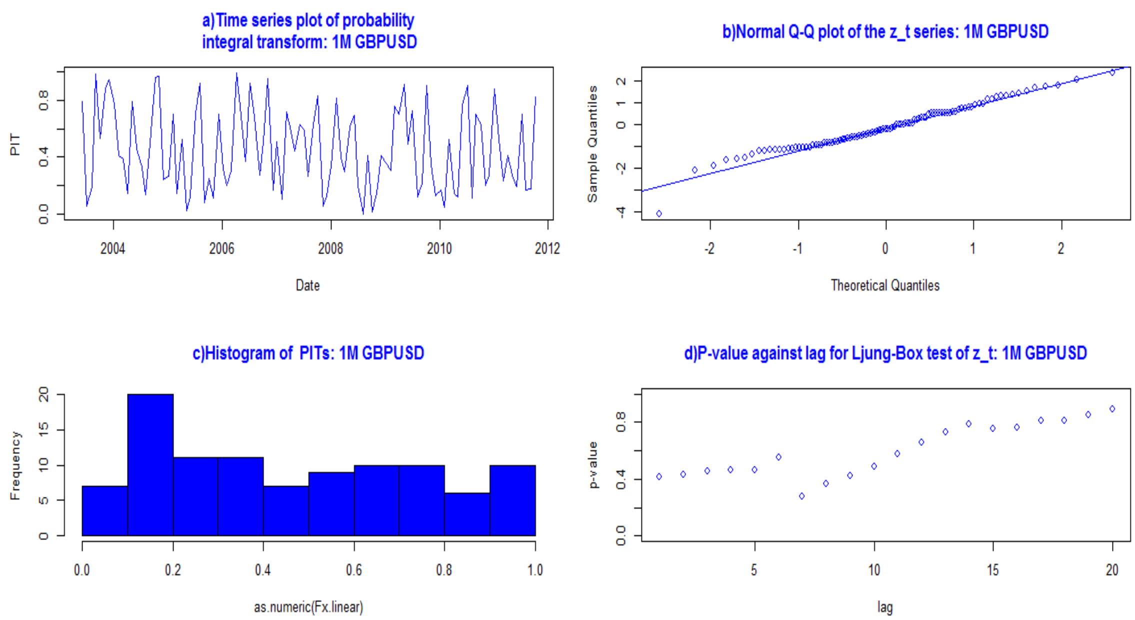


Figure 3.3: Empirical Properties of Extracted Probability Integral Transforms

(c) GBPUSD 1M



(d) USDCAD 1M

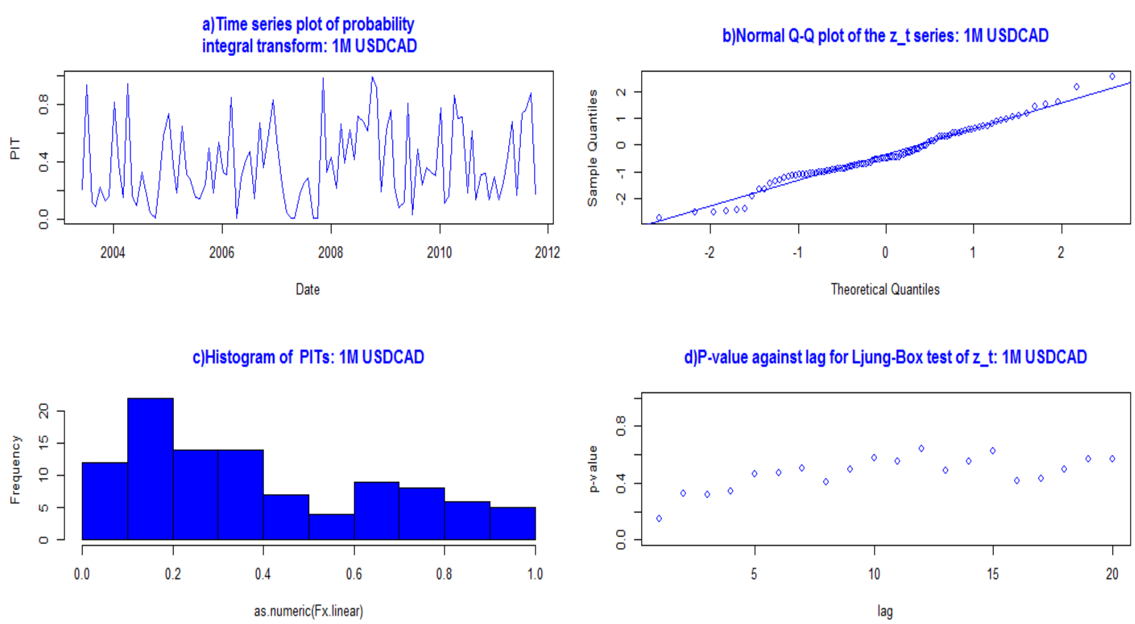


Figure 3.3: Empirical Properties of Extracted Probability Integral Transforms

(e) USDJPY 1M RET

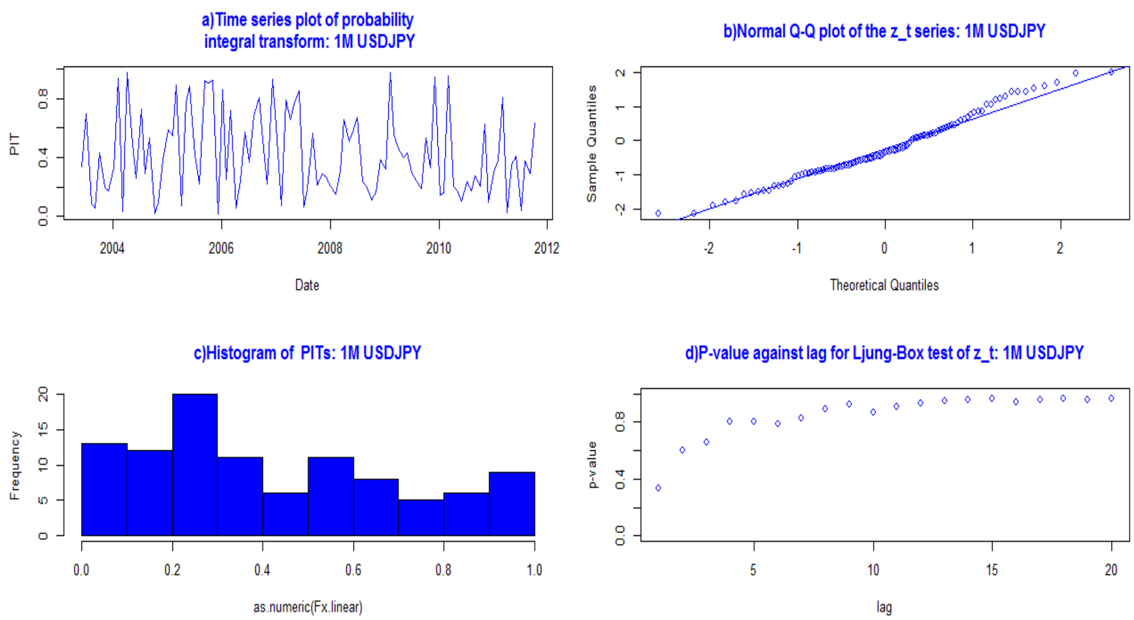


Table 3.1: O-T-C Market Statistics and Conventions

Quoting Conventions in over-the-counter FX Options Market

Symbol	Definition	Base currency	Domestic currency	Positive Skew means
AUDUSD	USD per AUD	AUD	USD	USD depreciation
EURUSD	USD per EUR	EUR	USD	USD depreciation
GBPUSD	USD per GBP	GBP	USD	USD depreciation
USDCAD	CAD per USD	USD	CAD	CAD depreciation
USDJPY	JPY per USD	USD	JPY	JPY depreciation

Sample Annualized Implied Volatilities

Tenor	ATM	25D RR	25D VWB	10D RR	10D VWB
1 Week	7.352	-0.495	0.131	-0.847	0.379
1 Month	6.851	-0.347	0.136	-0.584	0.389
2 Month	6.851	-0.366	0.157	-0.619	0.449
3 Month	6.851	-0.396	0.162	-0.663	0.485
6 Month	6.901	-0.426	0.187	-0.703	0.54
9 Month	7.051	-0.446	0.197	-0.743	0.571
12 Month	6.901	-0.426	0.187	-0.703	0.54

Average Daily Turnover in FX market (billions)

	1998	2001	2004	2007	2010	2013
Spot FX Transactions	568	386	631	1005	1488	2046
Percentage Change	N/A	-32	63.5	59.3	48.3	37.5
FX Derivatives						
Outright Forwards	128	130	209	362	475	680
FX Swaps	734	656	954	1714	1759	2228
Options and other products	**87**	**60**	119	**212**	**207**	**337**
Percentage Change	N/A	-31	98.3	83	-2.4	62.8
Exchange-Traded Derivatives	11	12	26	80	155	160

Note: "ATM" is at-the-money straddle, 25D RR and 10D RR are 25%- and 10%- delta risk reversals respectively; and 25D VWB and 10D VWB are 25%- and 10%- delta Vega-weighted butterflies respectively. See subsection (3.3.1) for more details.

.1 *Expressions for Option-Implied Risk-Neutral Moments*

In this section, we give the expressions for $V(t,\tau)$,$W(t,\tau)$, $X(t,\tau)$ and $\mu(t,\tau)$used in equation (2.3.10). Derivations can be found in Bakshi et al. (2003b) and Grad (2010).

$$V(t,\tau) = \int_{\bar{S}}^{\infty} \frac{2(1 - ln[\frac{K}{\bar{S}}])}{K^2} C(t,\tau,K)dK + \int_{0}^{\bar{S}} \frac{2(1 + ln[\frac{\bar{S}}{K}])}{K^2} P(t,\tau,K)dK \tag{.1.1}$$

$$W(t,\tau) = \int_{\bar{S}}^{\infty} \frac{6ln[\frac{K}{\bar{S}}] - 3(ln[\frac{K}{\bar{S}}])^2}{K^2} C(t,\tau,K)dK - \int_{0}^{\bar{S}} \frac{6ln[\frac{\bar{S}}{K}] + 3(ln[\frac{\bar{S}}{K}])^2}{K^2} P(t,\tau,K)dK \tag{.1.2}$$

$$X(t,\tau) = \int_{\bar{S}}^{\infty} \frac{12(ln[\frac{K}{\bar{S}}])^2 - 4(ln[\frac{K}{\bar{S}}])^2}{K^3} C(t,\tau,K)dK + \int_{0}^{\bar{S}} \frac{12ln[\frac{\bar{S}}{K}] + 4(ln[\frac{\bar{S}}{K}])^3}{K^2} P(t,\tau,K)dK \tag{.1.3}$$

where

$$\mu(t,\tau) = \mathbb{E}_t\left(ln\left[\frac{S_{t+\tau}}{S_t}\right]\right) = e^{r^d\tau} - 1 - \frac{e^{r^d\tau}}{2}V(t,\tau) - \frac{e^{r^d\tau}}{6}W(t,\tau) - \frac{e^{r^d\tau}}{24}X(t,\tau). \tag{.1.4}$$

.2 *Deriving the coefficients in the Malz quadratic specification*

The Malz quadratic specification is :

$$\hat{\sigma}_\delta(\delta_{call}) = b_0 atm_t + b_1 rr_t(\delta_{call} - 0.50) + b_2 vwb_t(\delta_{call} - 0.50)^2 \tag{.2.1}$$

Assuming the delta of an at-the-money option is exactly 0.5, I have: $atm = b_0 atm_t$, which gives $b_0 = 1$. Next, from the expression for $\sigma_{call}(0.25)$, I have

$$\sigma_{call}(0.25) = vwb_t + atm_t + \frac{rr_t}{2} \tag{.2.2}$$

From the expression for $\sigma_{put}(0.25)$, I have

$$\sigma_{put}(0.25) = vwb_t + atm_t - \frac{rr_t}{2} = \sigma_{call}(0.75) \tag{.2.3}$$

Plugging (.2.2) into (.2.1), I get:

$$vwb_t + atm_t + \frac{1}{2}rr_t = atm - b_1\frac{rr_t}{4} + \frac{2b_2vwb_t}{16}, \tag{.2.4}$$

and plugging (.2.3) into (.2.1) I get

$$vwb_t + atm_t - \frac{rr_t}{2} = atm + b_1\frac{rr_t}{4} + \frac{2b_2vwb_t}{16} \tag{.2.5}$$

Subtracting (.2.5) from (.2.4) yields

$rr_t = \frac{-b_1 rr_t}{2}$, or $b_1 = -2$. Lastly, adding (.2.4) to (.2.5) yields

$$2vwb_t + atm_t = atm + \frac{2b_2vwb_t}{16}, \tag{.2.6}$$

which gives us $b_2 = 16$.

BIBLIOGRAPHY

Aydin, H.I., A. DeGerli, and P. Ozlu (2010), "Recovery risk-neutral densities from exchange rate options: Evidence from turkey." *Central Bank of Turkey WP 1003*.

Bacchetta, P. and E. van Wincoop (2009), "Predictability in financial markets:what do survey data tell us?" *Journal of International Money and Finance*, 28, 406–426.

Bahra, B. (1997), "Implied risk-neutral density functions from option prices:theory and applications." *Bank of England Working Paper*.

Bai, J. and P. Perron (2003), "Computation and analysis of multiple structural change models." *Journal of Applied Econometrics*, 18, 1–22.

Bakshi, G., N. Kapadia, and D. Madan (2003a), "Stock return characteristics,skew laws, and the differential pricing of individual equity options." *Review of Finacial Studies*, 6, 101–143.

Bakshi, G., N. Kapadia, and D. Madan (2003b), "Stock return characteristics,skew laws, and the differential pricing of individual equity options." *Review of Finacial Studies*, 6.

Berkowitz, J. (2001). *Journal of Business and Economic Statistics*, 19, 465–474.

Bilson, J.F. (1981), "The "speculative effiency" hypothesis." *Journal of Business*, 54.

Black, F. and M. Scholes (1973), "The pricing of corporate liabilities." *The Journal of Political Economy*, 81, 637–654.

Breeden, D. and R. Litzenberger (1978), "Prices of state contingent claims implicit in options." *Journal of Business*, 51, 621–652.

Brinkmann, F., A. Kempf, and O. Korn (2014), "Forward-looking measures of higher order dependencies." *SRRN Working Paper http://dx.doi.org/10.2139/ssrn.2385228*.

Burnside, C., M. Eichenbaum, I. Kleschchelski, and S. Rebelo (2011), "Do peso problems explain the returns to the carry trade?" *Review of Financial Studies*, 24, 853–891.

Byoun, S, C.C.Y. Kwok, and H.Y. Park (2003), "Expectation hypothesis of the term structure of implied volatility:evidence from foreign currency and stock index options." *Journal of Financial Econometrics*, 1, 126–151.

Campa, J.M., , and Chang K.P.H. (1998), "Learning from the term structure of implied volatility." In *Currency Options and Exchange Rate Economics* (Zhaohui Chen, ed.), 183–195, World Scientific.

Campa, J.M. and K. Chang (1998), "The forecasting ability of correlations implied in foreign exchange options." *Journal of International Money and Finance*, 17.

Carr, P. and D. Madan (2001), "Optimal positioning in dervative securities." *Quantitative Finance*, 1, 19–37.

Castagna, A. (2010), *FX Options and Smile Risk*. WILEY, United Kingdom.

Castagna, Antonio and Fabio Mercurio (2005), "Consistent pricing of fx options." *SSRN Working Paper No 873788.*

Castagna, M. and F. Mercurio (2007), "The vanna-volga method for implied volatilities." *Risk*, 20, 106–111.

Castren, O. (2005), "Estimating and analyzing options implied risk-neutral density functios for the largest new eu member states." *European Central Bank Working Ppaer 440.*

Chen, Y-c. and K-P. Tsang (2013), "What does the yield curve tell us about exchange rate predictability." *Review of Economics and Statistics*, 95, 185–205.

Chen, Z. (1998), "Learning from option markets." In *Currency Options and Exchange Rate Economics* (Zhaohui Chen, ed.), 3–6, World Scientific.

Cincibuch, Martin and David Vavra (2004), "Testing for uncovered interest parity using distributions implied by fx options." *Czech National Bank working paper.*

Clarida, R.H., L. Sarno, M.P Taylor, and G. Valente (2003), "The out-of-sample success of term structure models as exchange rate predictors:a step beyond." *Journal of International Economics*, 60, 61–83.

Clarida, R.H. and M.P. Taylor (1997), "The term structure of forward exchange rate premiums and the forecastability of spot exchange rates:correcting the errors." *Review of Economics and Statistics*, 79, 353–361.

Csavas, C. (2008), "Density forecast evaluation and the effect of risk-neutral central moments on the risk premium." *Magyar Nemzeti Bank Working Paper*.

Cumby, R.E. and M. Obstfeld (1984), "International interest rate and price level linkages under flexible exchange rates: A review of recent evidence." In *Exchange Rate Theory and Practice* (J.F.0 Bilson and R.C. Marston, eds.), 121–51, National Bureau of Economic Research Conference Report,University of Chicago Press.

Diebold, F.X., T.A. Gunther, and A.S. Tay (1998), "Evaluating density forecasts with applications to financial risk management." *International Economic Review*, 39, 863–883.

Diebold, F.X., Piazzesi M., and Rudebusch G.D. (2005), "Modeling bond yields in finance and macroeconomics." *American Economic Review*, 95, 415–420.

Engel, C. (1996), "The forward discount anomaly and the risk premium: A survey of recent evidence." *Journal of Empirical Finance*, 3, 123–192.

Engel, C. and K. D. West (2005), "Exchange rates and fundamentals." *Journal of Political Economy*, 113, 485–517.

Engel, Charles (2013), "Exchange rates and interest parity." In *Handbook of International Economics,vol. 4,Forthcoming* (Gita Gopinath, Elhanan Helpman, and Kenneth Rogoff, eds.), Elsevier.

Evans, M.D. and K. Lewis (1995), "Do long term swings in the dollar affect estimates of the risk premia?" *Review of Financial Studies*, 8, 709–42.

Eviews (2013), "Eviews 8 guide ii."

Fama, E. and K. R. French (1993), "Common risk factors in the returns on stocks and bonds." *Journal of Financial Economics*, 33, 3–56.

Fama, Eugene F. (1984), "Forward and spot exchange rates." *Journal of Monetary Economics*, 14, 319–38.

Garman, M.B and S.W. Kohlhagen (1983), "Foreign currency option values." *Journal of International Money and Finance*, 2, 231–237.

Gereben, A. (2002), "Extracting market expectations from option prices:an application to over-the counter new zealand dollar options." *New Zealand Central Bank Working Paper*.

Grad, D. (2010), "Foreign exchange risk premia and macroeconomic announcements:evidence from overnight currency options." *Unpublished Dissertation Chapter*.

Hansen, L. P. and R.J. Hodrick (1980), "Forward rates as unbiased predictors of future spot rates." *Journal of Political Economy*, 99, 461–70.

Hodrick, R.J. and S. Srivastava (1984), "An investigation of risk and return in forward foreign exchange." *Journal of International Money and Finance*, 3.

Jackwerth, J.A. (2000), "Recovering risk aversion from option prices and realize returns." *Review of financial studies*, 13, 433–451.

Jondeau, Eric, Ser-Huang Poon, and Michael Rockinger (2010), *Financial Modeling under non-gaussian distributions*. Springer, United States.

Jurek, J. (2009), "Crash-neutral currency carry trades." *Princeton University Working Paper*.

Koenker, Roger and Jose Machado (1999), "Goodness of fit and related inference processes for quantile regression." *Journal of the American Statistical Association*, 94, 1296–310.

Krasker, W.S. (1980), "The "peso problem" in testing the efficiency of forward exchange markets." *Journal of Monetary Economics*, 6, 269–276.

Lewis, K. (1989), "Changing beliefs and systematic rational forecast errors with evidence from foreign exchange." *American Economic Review*.

Lustig, H., N. Roussanov, and A. Verdelhan (2011), "Common risk factors in currency markets." *Review of Financial Studies*, 24, 3731–3777.

Malz, A. (1998), "Option prices and the probability distribution of exchange rates." In *Currency Options and Exchange Rate Economics* (Zhaohui Chen, ed.), 108–137, World Scientific.

Malz, A.M. (1997), "Option-implied probability distributions and currency excess returns." *Federal Reserve Bank of New York Staff Report*, 32.

Mark, N. (1995), "Exchange rates and fundamentals:evidence on long-horizon predictability." *American Economic Review*, 85, 201–218.

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.

Mixon, Scott (2007), "The implied volatility term structure of stock index options." *Journal of Empirical Finance*, 14, 333–354.

of International Settlements, Bank (2013), "Foreign exchange turnover in april 2013: preliminary global results."

Renaud, Olivier and Maria-Pia Victoria-Fraser (2010), "A robust coefficient of determination for regression." *Journal of Statistical Planning and Inference*, 142, 1852–1862.

Sarno, L. and G. Valente (2005), "Empirical exchange rate models and currency risk:some evidence from density forecasts." *Journal of International Money and Finance*, 24, 363–385.

Sarno, S. and M.P. Taylor (2002), *The economics of exchange rates*. Cambridge, United Kingdom.

Scott, R.C. and P.A. Horvath (1980), “On the direction of preference for moments of higher order than the variance.” *Journal of Finance*, 35, 915–919.

Siegel, A. F. (1997), “International currency relationship information revealed by cross-option relationships.” *Journal of Futures Markets*, 17, 369–384.

Stein, Jeremy (1989), “Overreactions in the options market.” *Journal of Finance*, 44, 1101–1023.

Verdelhan, A. (2012), “The share of systematic variation in bilateral rates.” *Working Paper*.

Walter, Christian and Jose A. Lopez (2000), “Is implied correlation worth calculating? evidence from foreign exchange options.” *Journal of Derivatives*, 7, 65–81.

Zivot, E. and D. W. K. Andrews (1992), “Further evidence on the great crash,the oil price shock and the unit root hypothesis.” *Journal of Business and Economic Statistics*, 10, 251–271.