FX Options and Excess Returns

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Abstract

The empirical failure of the uncovered interest rate parity (UIP) condition has been commonly attributed to underlying time-varying risk premia and market expectation biases. Neither of these concepts can be reliably measured empirically. Our paper uses market prices of FX options to capture common assessment of the probability distributions of future exchange rate realizations, and shows that the distributional moments implied by options prices consistently explain subsequent excess currency returns or deviations from UIP. Using daily options data for five major currency pairs over the period 2007 through 2011, we show that the options-implied FX risk measures - standard deviation, skewness, and kurtosis - can explain subsequent FX excess returns for horizons between one week to twelve months. Pushing beyond matched-frequency UIP-style analyses, we further show that 1) the term structure of options-implied moments and 2) information incorporating a broader set of FX currency options, can both help predict quarterly bilateral excess returns, supporting previous literature emphasizing term-structure dynamics and global risk. Lastly, we find that the 2008 financial crisis induces a major structural break in the empirical relationship between options-implied moments and currency risk.

Keywords: Excess returns, Volatility smile, Term structure of implied moments, Option-implied correlation

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1. **Introduction**

The forward exchange rate is well-known to be a biased predictor of the future spot rate, an empirical regularity commonly referred to as the forward premium puzzle or the uncovered interest parity (UIP) puzzle. One manifestation of this empirical (ir)regularity is that countries with higher interest rates tend to see their currencies appreciate subsequently, and a "carry-trade" strategy exploiting this pattern, on average, deliver excess currency returns.[1] This violation of the UIP condition is commonly attributed to time-varying risk premium and biases in (measured) market expectations. However, empirical proxies based on surveyed forecasts or standard measures of risk –e.g. ones built from consumption growth, stock market returns, or the Fama-French (1993) factors – have been unsuccessful in explaining it.[2] As such, while recognizing the presence of risk, macro exchange rate modeling efforts often ignore it in empirical testing (e.g. Mark 1995; Engel and West 2005). 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 (e.g. Lustig and Verdelhan 2007; Lustig et al 2011).[3]

This paper proposes to use information in the currency (FX) option prices to construct measures of expected risk, and test whether option-implied higher-moment risks explain subsequent excess returns. Conceptually, since payoffs of option contracts depend on the uncertain future realization of the price of the underlying asset, option prices must reflect market sentiment and beliefs about the probability of future payoffs. Using prices of a cross section of

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

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

[3] Lustig and Verdelhan (2011) and Verdelhan (2012) for example identify a "carry factor" based on cross-section of interest rate sorted currency returns, and a "dollar factor" based on cross-section of dollar beta-sorted currency returns.

option contracts (at-the-money, risk reversals and vega-weighted butterflies at 10- and 25 deltas) each deliver payoffs under differential future realizations, we uncover ex-ante standard deviations, skewness, and kurtosis of expected future exchange rate changes. With daily options data for five major currency pairs and seven tenors, we show that these market-based measures of FX variance, crash, and tail risk can explain subsequent FX excess returns between horizons of one week and 12 months. We then extend the approach pioneered by Hansen and Hodrick (1980), and in Clarida and Taylor (1997), Chen and Tsang (2009) that use the forward rates or interest differentials over time and across currency pairs to model excess returns.

We note that simple derivatives such as the forwards and futures have been used extensively in explaining excess returns (e.g. Hansen and Hodrick 1980, Clarida and Taylor 1997 among many others). However, payoffs from forward contracts 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. Indeed, FX options have been used to proxy variance or tail risk in various specific but limited context, such as testing the portfolio balance model of exchange rate determination (Lyons,1988), measuring announcements effects (Grad, 2010), evaluating rare events theory (Farhi et.al,2009), or conducting density forecasts (Christoffersen and Mazzota, 2005). To the best of our knowledge, however, there has been no systematic and comprehensive testing of whether the information contained in ex-ante FX options indeed predicts ex-post excess currency returns. Our paper aims to bridge this gap.

Our use of options price data and related empirical methodologies is motivated by a number of reasons. First, options are forward-looking by construction. Campa, Chang and Reider (1998) point out that this forward-looking property means options prices should incorporate information such as forthcoming regime switches or the presence of a peso problem.[4] Options prices are also rooted in market participant behavior as they are based on what market participants do instead of what they say.[5] Furthermore, cross sections of option-prices imply a subjective probability distribution of future spot exchange rates, which captures both market participants' beliefs and their preferences. (This distribution is commonly referred to as the "risk-neutral distribution", though it does NOT imply it's 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.)

Modern techniques such as the Vanna-Volga method (see, e.g. Castagna and Mercurio 2005) and the methodology of Bakshi, Kapadia and Madan (2003) facilitate elegant computation of options-implied higher order moments of future exchange rate changes. These methods are particularly attractive because the options-implied moments are extracted without having to impose any assumptions on investor preferences and expectation-formation mechanisms, or to specify the stochastic process driving the underlying spot exchange rate.

Lastly, option prices are an attractive source for extracting market expectations when compared to other sources commonly considered for the same purposes. For example, Chen and Goodhart (1997) argue that FX options markets are likely to contain cleaner measures of market expectations than interest rate differentials because there is less government intervention in these markets. Survey data are based on what market participants say, not what they do, and their

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[4] 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 average excess return.

[5] Contrast with say, survey data.

coverage is confined to a subset of survey participants instead of being an aggregate of the whole market.[6]

Our main empirical results are as follows: first, there are significant breaks in the relationship between the moments in 2008. Third, risk-neutral moments appear to be quite robust in predicting ex-post FX excess returns, so is the information extracted from a panel of currency options across countries and across tenors. We find that the term structure of options-implied moments as well as combined options information from a broader set of currencies both help predict bilateral excess returns.

2. Theoretical Background and Empirical Strategy

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:

$$i_t^\tau - i_t^{\tau,*} = E_t \Delta s_{t+\tau} + \rho_{t+\tau}$$

This condition is expected to hold for all investment horizon τ, with interest rates are at matched maturities. Ignoring the risk premium term, numerous papers have tested this equation since Fama 1980, and find systematical violations of this UIP condition:

$$\Delta s_{t+\tau} = \alpha + \beta(i_t - i_t^*) + \varepsilon_{t+\tau}$$
$$H_0: \beta = 1$$

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[6] As discussed earlier, forward contracts are forward-looking by construction, but for a given currency pair and tenor, there is only one forward price with linear dependency on future spot realization. The multiple option prices for options with different strike prices offer a much richer information set. Lastly, standard constructions of market expectations and perceived risks based on macro fundamentals or finance factors have not worked well.

With an estimated $\hat{\beta} < 0$. 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, equations the forward premium $f_t^{t+\tau} - s_t$, with interest differentials. The UIP condition above thus implies that the forward rate should be an unbiased predictor for future spot rate:

$$E_t s_{t+\tau} = f_t^{t+\tau} \text{ or } s_{t+\tau} = f_t^{t+\tau} + u_{t+\tau}$$

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:

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

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 iid normal over time. If the distribution of either of these are not normal mean zero over the time series, empirical estimates of the slope coefficient would likely suffer omitted variable bias or other complications.

The difficulty faced by the literature is that standard proposed measures of risk, such as ones based on real per-capita consumption growth (CAPM), excess returns in the equity markets, the Fama-French (1993) factors (excess returns in the stock market, the size premium, and the value premium), and so on do not appear to have strong correlation with excess returns. We will show next how to use information in the FX options market to construct proxies for market perceived volatility risk, and tail and crash risks.

2.2 Information Content of FX Volatility Surface

Volatility smile refers to a plot of implied volatility of options on a given underlying asset with a given maturity, at different strike prices. A starting point for understanding the information content of the volatility smile is the result by Breeden and Litzenberger (1978), who show the following relationship between the call options and exercise prices:

$$\frac{\partial^2 C}{\partial K^2} = e^{-r^d \tau} \pi_t^Q (S_T), \qquad (1)$$

where

- C is the price function of a European call option.
- K is the exercise/strike price
- r^d is the domestic risk-free interest rate
- τ is the tenor/time to maturity
- $\pi_t^Q(S_T)$ 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) implies that, in principle, we can estimate the whole pdf of time T spot exchange rate from time *t* volatility smile.

Additionally, 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, as shown from the following formula for the price of a European call option:

$$C(t, K, T) = \int_K^\infty M_{t,T} \, (S_T - K) \pi^P (S_T) dS_T = e^{-r^d \tau} \int_K^\infty (S_T - K) \, \pi^Q (S_T) dS_T. \qquad (2)$$

In the above equation,

- $M_{t,T}$ is the investor's stochastic discount factor, which captures the investor's degree of risk aversion.
- $\pi^P(S_T)$ 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:

$$\pi^Q(S_T) = e^{r^d\tau} M_{t,T} \pi^P(S_T) \quad . \tag{3}$$

Equation (3) illustrates that information about both market participants' beliefs ($\pi^P(S_T)$) and preferences ($M_{t,T}$) are embedded in the extracted option-implied the risk-neutral probability density.

Both forward contracts and currency options are forward-looking by construction. Furthermore, the risk-neutral density implied by the pricing equations for both derivatives is the same. For the purpose of making inferences about this density, however, the option price equation is more useful than the one for forward prices because for a given tenor and currency pair, a cross section of option prices with different strike prices are observed, whereas there is only one forward price observed for a given time to maturity. For a given currency pair, day and tenor we observe multiple prices for options with different strikes, whereas there is no cross sections of forward prices.

A forward contract can in fact be viewed as a European call option with an exercise price of zero. Therefore currency option prices should, at a minimum do as well as forward prices. The theoretical forward exchange rate is given by the formula:

$$\mathrm{F_{t,T}} = \mathrm{e}^{-\mathrm{r^d}\tau} \int_0^\infty \mathrm{S_T}\, \pi_t^Q(\mathrm{S_T}) \mathrm{dS_T} \tag{4}$$

Evaluating equation (2), the formula for the price of a call option, at $K = 0$ yields:

$$C(t,0,T) = e^{-r^d \tau}\mathbb{E}^Q(\max\ (S_T - \mathrm{K}, 0)) = e^{-r^d \tau}\int_0^\infty S_T\, \pi^Q(S_T)dS_T = F_{t,T}\ . \qquad 2(a)$$

In addition to the information contained in cross sections of option prices with a given tenor, the prices of options with same strike prices but ***different maturities*** potentially provide a second source of information regarding the market's expectations of evolution of spot exchange rates and the market's perception of risk.

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

$$\ln\left(\mathrm{S_{AB,t}}\right) = \ln\left(\mathrm{S_{AC,t}}\right) - \ln\left(\mathrm{S_{BC,t}}\right) = \mathrm{s_{AC,t}} - \mathrm{s_{BC,t}} \qquad (5)$$

The equation above implies that

$$\mathrm{Var}(\ \mathrm{s_{AB}}) = \mathrm{Var}(\mathrm{s_{AC}}) + \mathrm{Var}(\mathrm{s_{BC}}) - 2\rho\ (\mathrm{s_{AC}}, \mathrm{s_{BC}})\mathrm{Var}(\mathrm{s_{AC}})^{1/2}\mathrm{Var}(\mathrm{s_{BC}})^{1/2}, \qquad (6)$$

this can be rearranged to give:

$$\rho\ (\mathrm{s_{AC}}, \mathrm{s_{BC}}) = \frac{\mathrm{Var}(\mathrm{s_{AC}}) + \mathrm{Var}(\mathrm{s_{BC}}) - \mathrm{Var}(\ \mathrm{s_{AB}})}{2\mathrm{Var}(\mathrm{s_{AC}})^{1/2}\mathrm{Var}(\mathrm{s_{BC}})^{1/2}} \qquad (5a)$$

If we use option-implied variance to estimate the right hand side of equation (5a) , then the resulting estimate of $\rho\ (\mathrm{s_{AC}}, \mathrm{s_{BC}})$ is option-implied correlation. Siegel (1997) points out that this option-implied correlation reveals market sentiment regarding how closely the currencies are expected to move in the future. We interpret these option-implied correlations as capturing global risk.

2.3 Extracting FX Option-Implied Risk–Neutral Moments

2.3.1 Review of Methodologies for Extracting Risk-Neutral Pdfs.

Most of the techniques for estimating option-implied state price densities build on the Breeden-Lichtenberger result in equation (1) . Bahra(1997) groups these methods into four broad categories:

- Methods that make assumptions about the stochastic process followed by the underlying asset and then infer the state price density from that process
- Methods that make a parametric assumption regarding the state price density and recover its parameters by minimizing the distance between observed option prices and prices generated by the assumed state price density function.
- Methods that derive the state price density function directly from a specification of the implied volatility curve.
- Methods that estimate the state price density function non-parametrically by not making any parameter restrictions on the on the underlying asset, the call price function or the state price density.

Implementation of the Breeden-Litzenberger result requires a continuous volatility smile function, whereas FX options are only traded for a discrete number of exercise prices for each tenor. Castagna (2010) proposes three criteria for selecting a representation of the volatility surface: parsimony, consistency and intuitiveness.

The parsimony criterion emphasizes that the representation 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.

Our choice of the Vanna Volga method (henceforth VV), explained in the next section, is guided by the above criteria. The VV methodology is parsimonious because it uses only three option combinations to build an entire volatility smile. 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.[7] The VV method also has a solid financial motivation: Castagna and Mercurio (2005) show that 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, a being delta-neutral, is also Vega-neutral. In situations where volatility is stochastic, it might be useful to construct portfolios that, in addition to hedging against changes in the price of the underlying asset, the investor also hedge against for the Vega$\left(\frac{\partial C}{\partial \sigma}\right)$, the Vanna $\left(\frac{\partial^2 C}{\partial^2 \sigma}\right)$ and the Volga$\left(\frac{\partial^2 C}{\partial \sigma \partial S}\right)$ as might be necessary in situations when volatility is stochastic.

2.3.2 The Vanna-Volga and Bakshi et.al (2003) Methodologies

We use the methodology of Bakshi, Kapadia and Madan(2003) (henceforth BKM) to extract model-free option-implied standard deviation, skewness and kurtosis from the volatility smile. Grad (2010) and Jurek (2007) also use the BKM methodology to extract options-implied higher order moments. In this section we closely follow Grad's exposition and notation.

The extracted moments using the BKM methodology are model-free because we make no assumptions regarding the time series process governing the underlying spot exchange rate. The model-free nature of the methodology is attractive because it means the methodology is equally applicable to all exchange rate regimes. Campa, Chang and Reider (1998) argue that having a methodology that does not presuppose a stochastic process followed by the underlying spot exchange rate is especially useful in situations where the FX regime is unknown or changing, or when the degree of government intervention is unclear.

The BKM methodology rests on the results of Bakshi and Madan (2000), which show that if we have an arbitrary claim with a pay-off function H[S] with finite expectations, then H[S] can be

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[7] The three particular option combinations used, the ATM straddle, Vega-weighted butterfly capture these movements. See discussions in Castagna(2010) and Malz(1997)

replicated if we have a continuum of option prices. They also show that if H[S] is twice-differentiable, then it can be spanned by the following expression:

$$\mathrm{H[S]}=\mathrm{H}[\bar{\mathrm{S}}]+(\mathrm{S}-\bar{\mathrm{S}})\frac{\partial \mathrm{H}}{\partial \mathrm{S}}+\int_{\bar{\mathrm{S}}}^{\infty}\frac{\partial^2 \mathrm{H}}{\partial \mathrm{S}^2}\max(\mathrm{S}-\mathrm{K},0) \quad +\int_0^{\bar{S}}\frac{\partial^2 H}{\partial S^2}\max\,(K-S,0)\,dK. \tag{7}$$

Assuming no arbitrage opportunities, the price of a claim with pay-off H[S] is given by the expression:

$$\begin{aligned} \mathrm{p_t} &= e^{-r^d\tau}\mathbb{E}(\mathrm{H[S]}) \\ &= (H[\bar{S}]-\bar{S}\frac{\partial H}{\partial S}[\bar{S}])e^{-r^d\tau}+\frac{\partial H}{\partial S}Se^{-r^d\tau}+\int_{\bar{S}}^{\infty}\frac{\partial^2 H}{\partial S^2}C(t,\tau,K)+\int_0^{\bar{S}}\frac{\partial^2 H}{\partial S^2}P(t,\tau,K)\,dK, \end{aligned} \tag{8}$$

where

- K is the exercise price.
- $C(t,\tau,K)$ is the price of a European–style call option with strike K and tenor τ.
- $P(t,\tau,K)$ is the price of a European-style put option with strike K and tenor τ.
- $\bar{S}$ is some constant, usually chosen to equal current spot price.

Equation (8) says that any pay-off function H[S] can be replicated by a portfolio of calls, puts, risk-free domestic bonds and the spot rate, with the weight placed on each asset in this replicating portfolio depends on the pay-off function H[S]. If we let $R_t = \ln\left(\frac{S_{t+1}}{S_t}\right)$, then to get expressions for the second, third and fourth non-central moments of future exchange rate changes, one defines contracts with pay-offs given in equation (10) below, price each of these hypothetical contracts using equation (9) and remove the discounting.[8]

$$\mathrm{H[S]}=\begin{cases}[\mathrm{R_t(S)}]^2 \text{ Volatility Contract}\\ [\mathrm{R_t(S)}]^3 \text{ Cubic Contract}\\ [\mathrm{R_t(S)}]^4 \text{ Quartic Contract}\end{cases} \tag{9}$$

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[8] As an example, $\mathbb{E}([\mathrm{R_t(S)}]^2 = e^{r^d\tau}\mathrm{p_t}$.

BKM show that the expressions for the second, third and fourth non-central moments, which also reflect the prices of the volatility, cubic and quartic contracts, are given by

$$V(t,\tau) = \int_{\bar{S}}^{\infty} \frac{2\left(1-\ln\left(K/_{\bar{S}}\right)\right)}{K^2} C(t,\tau,K)dK + \int_{0}^{S(t)} \frac{2\left(1+\ln\left(\bar{S}\ /K\right)\right)}{K^2} P(t,\tau,K)dK\,, \qquad (10)$$

$$W(t,\tau) = \int_{S(t)}^{\infty} \frac{6\ln\left(K/_{\bar{S}}\right) - 3\left[\ln\left(K/_{\bar{S}}\right)\right]^2}{K^2} C(t,\tau,K)dK - \int_{0}^{S(t)} \frac{6\ln\left(\bar{S}/_K\right) + 3\left[\ln\left(\bar{S}/_K\right)\right]^2}{K^2} P(t,\tau,K)dK, \qquad (10b)$$

$$X(t,\tau) = \int_{\bar{S}}^{\infty} \frac{12\left[\ln\left(K/_{\bar{S}}\right)\right]^2 - 4\left[\ln\left(K/_{\bar{S}}\right)\right]^3}{K^2} C(t,\tau,K)dK + \int_{0}^{\bar{S}} \frac{12\left[\ln\left(\bar{S}/_K\right)\right]^2 + 4\left[\ln\left(\bar{S}/_K\right)\right]^3}{K^2} P(t,\tau,K)dK\,. \qquad (10c$$

Once the non-central moments are extracted, the variance, skewness and kurtosis of the distribution of future exchange rate changes can be calculated using the following formulas in BKM:

$$Var(\,t,\tau) = e^{r^d\tau}V(t,\tau) - \mu(t,\tau)^2 \qquad (11)$$

$$Skew(t,\tau) = \frac{e^{r^d\tau}W(t,\tau) - 3V\mu(t,\tau)e^{r^d\tau} + 2\mu(t,\tau)^3}{\left[e^{r^d\tau}V(t,\tau) - \mu(t,\tau)^2\right]^{3/2}} \qquad (111b)$$

$$Kurt(t,\tau) = \frac{e^{r^d\tau}X(t,\tau) - 4e^{r^d\tau}\mu(t,\tau)W(t,\tau) + 6e^{r^d\tau}\mu(t,\tau)^2V(t,\tau) - 3\mu(t,\tau)^4}{\left[e^{r^d\tau}V(t,\tau) - \mu(t,\tau)^2\right]^2}, \qquad (11c)$$

where

$$\mu(t,\tau) = e^{r^d\tau} - 1 - \frac{e^{r^d\tau}}{2}V(t,\tau) - \frac{e^{r^d\tau}}{6}W(t,\tau) - \frac{e^{r^d\tau}}{24}X(t,\tau). \qquad (11d)$$

The BKM methodology requires a continuum of exercise prices. However, in the o-t-c 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-σ) pairs by interpolation and extrapolation. To this end, we use the 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) show that if we have three options with implied volatilities 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 can be accurately approximated by the following expression:

$$\sigma(\mathrm{K}) = \sigma_2 + \frac{-\sigma_2 + \sqrt{\sigma_2^2 + \mathrm{d}_1(\mathrm{K})\mathrm{d}_2(\mathrm{K})(2\sigma_2 \mathrm{D}_1(\mathrm{K}) + \mathrm{D}_2(\mathrm{K}))}}{\mathrm{d}_1(\mathrm{K})\mathrm{d}_2(\mathrm{K})} \tag{12}$$

where:

$$\mathrm{D}_1(\mathrm{K}) = \frac{\ln\left({}^{\mathrm{K}_2}/_{\mathrm{K}}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}}\right)}{\ln\left({}^{\mathrm{K}_2}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_1}\right)}\sigma_1 + \frac{\ln\left({}^{\mathrm{K}}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}}\right)}{\ln\left({}^{\mathrm{K}_2}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_2}\right)}\sigma_2 + \frac{\ln\left({}^{\mathrm{K}}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}}/_{\mathrm{K}_2}\right)}{\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_2}\right)}\sigma_3 - \sigma_2 \tag{11b}$$

$$\mathrm{D}_2(\mathrm{K}) = \frac{\ln\left({}^{\mathrm{K}_2}/_{\mathrm{K}}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}}\right)}{\ln\left({}^{\mathrm{K}_2}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_1}\right)}\mathrm{d}_1(\mathrm{K}_1)\mathrm{d}_2(\mathrm{K}_1)(\sigma_1 - \sigma_2)^2 + \frac{\ln\left({}^{\mathrm{K}}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}}/_{\mathrm{K}_2}\right)}{\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_1}\right)\ln\left({}^{\mathrm{K}_3}/_{\mathrm{K}_2}\right)}\mathrm{d}_1(\mathrm{K}_3)\mathrm{d}_2(\mathrm{K}_3)(\sigma_2 - \sigma_3)^2 \tag{11c}$$

$$\mathrm{d}_1(\mathrm{x}) = \frac{\log\left(\left(\frac{\mathrm{S}_\mathrm{t}}{\mathrm{x}}\right) + (\mathrm{r}^\mathrm{d} - \mathrm{r}^\mathrm{f} + \frac{1}{2}\sigma_2)\tau\right.}{\sigma_2\sqrt{\tau}},\ \mathrm{d}_2(\mathrm{x}) = \mathrm{d}_1(\mathrm{x}) - \sigma_2\sqrt{\tau}\,, \text{for } \mathrm{x} \epsilon \{\mathrm{K}, \mathrm{K}_1, \mathrm{K}_2, \mathrm{K}_3\} \tag{11d}$$

Expression (12) 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 $K_3 = K_{25\Delta c}$.

2.4 Option-Implied Higher Order Moments and Currency Excess Returns

Following Csavas (2008) and Gereben (2002), we run OLS regressions with options-implied moments as explanatory variables and the dependent variable being FX forward bias:

$$\mathrm{F}_\mathrm{t}^{\mathrm{t}+\tau} - \mathrm{E}_\mathrm{t}(\mathrm{S}_{\mathrm{t}+\tau}) = \gamma_0 + \gamma_{1,\tau} * \mathrm{STDEV}_{\mathrm{t},\tau} + \gamma_{\mathrm{t},\tau} * \mathrm{SKEW}_{\mathrm{t},\tau} + \gamma_{\mathrm{t},\tau} * \mathrm{KURT}_{\mathrm{t},\tau} + \mathrm{u}_{\mathrm{t},\tau}. \tag{13}$$

Our motivation for running the above regression equation is similar to that in Gereben (2002):On one hand, currency excess returns are usually explained as resulting from time-varying FX risk premia. On the other hand, option-implied higher order moments are capture the nature of FX risk as perceived by the market: standard deviation captures expected volatility, skewness captures perceived asymmetry in the distribution of future spot rate or crash risk, and kurtosis captures perceived likelihood of large movements or tail risk. If currency excess returns are indeed due to time-varying risk premia, then variables that capture the nature of that risk should be able to explain time variation in the excess returns.

In equation (13) , $E_t(S_{t+\tau})$ is not observable. We use $S_{t+\tau}$, the observed spot rate at time $t+\tau$, as an estimate. The motivation for using $S_{t+\tau}$ as a proxy for $E_t(S_{t+\tau})$ is also given in Gereben(2002): if market participants have rational expectations, then $E_t(S_{t+\tau})$ and $S_{t+\tau}$ will differ by a forecast error ν_t that is uncorrelated with all variables that use information at time *t*:

$$\mathrm{S_{t+\tau}} = \mathrm{E_t(S_{t+\tau})} + \nu_t \tag{14}$$

Plugging (14) into (13) and rearranging, we get the following regression equation:

$$\mathrm{F_t^{t+\tau}} - \mathrm{S_{t+\tau}} = \gamma_{0,\tau} + \gamma_{1,\tau} * \mathrm{STDEV_{t,\tau}} + \gamma_{2,\tau} * \mathrm{SKEW_{t,\tau}} + \gamma_{3,\tau} * \mathrm{KURT_{t,\tau}} + \varepsilon_{t+\tau} \tag{13a}$$

where $\varepsilon_t = u_t + \nu_t$. Finally, to make the interpretation of the regression coefficients easier, we use $f_t^{t+\tau} - s_{t+\tau} = \log\left(\frac{F_t^{t+\tau}}{S_{t+\tau}}\right)$ as the dependent variable, so that our final regression specification is :

$$f_t^{t+\tau} - s_{t+\tau} = \gamma_{0,\tau} + \gamma_{1,\tau} * STDEV_{t,\tau} + \gamma_{2,\tau} * SKEW_{t,\tau} + \gamma_{3,\tau} * KURT_{t,\tau} + \varepsilon_{t+\tau} \tag{13b}$$

We use Newey-West standard errors to correct for auto-correlation resulting from our use of overlapping data.

2.5 Revisiting the UIP Puzzle : Augmented-UIP Regressions

The UIP condition implies that if market participants have rational expectations and are risk neutral, and that if the no-arbitrage condition of covered interest parity (CIP) holds, then the forward exchange is an unbiased predictor of the future spot rate:

$$F_t^{t+\tau} = \mathbb{E}_t^Q(S_{t+\tau}) \tag{15}$$

The UIP condition can be tested empirically. Empirical tests of the UIP condition usually take the form of the following regression:

$$(s_{t+\tau} - s_t) = \alpha + \beta(f_t^{t+\tau} - s_t) + \varepsilon_{t+\tau}, \tag{16}$$

If market participants have rational expectations and are risk-neutral, then it should be the case that $\alpha = 0$ and $\beta = 1$. Empirical estimations of equation (16), however, consistently yielded estimates of β that are closer to -1 than to 1. Such equations have also been unable to explain the variation of exchange rate changes, with R^2s ranging from 0.00 to 0.04 (Clarida and Taylor ,1997), which suggests that the forward premium, $(f_t^{t+\tau} - s_t)$, contains little or no information concerning the future dynamics of the spot exchange rate.

We first run the following augmented-UIP regression:

$$(s_{t+\tau} - s_t) = \alpha + \beta(f_t^{t+\tau} - s_t) + \gamma_1 * STDEV_{t,\tau} + \gamma_2 * SKEW_{t,\tau} + \gamma_3 * KURT_{t,\tau} + \varepsilon_{t+\tau}, \tag{17}$$

The intuition of the above equation is as follows: On one hand, the UIP puzzle is commonly attributed to time-varying risk premia. On the other hand, moments of the options-implied state price density are understood to capture FX risk, in particular, volatility risk, crash risk and tail risk. We therefore test whether controlling for these risk measures gives us a coefficient of β closer to one. Since these moments are obtained without having to assume that market participants have rational expectations, our framework allows get a cleaner test of the "time-varying risk premia" explanations of the UIP puzzle.

We then run UIP regressions with break indicator variables and interactions:

$$(s_{t+\tau} - s_t) = \alpha + D1 + \beta(f_t^{t+\tau} - s_t) + \mathrm{D1} * \delta_1(f_t^{t+\tau} - s_t) + \varepsilon_{t+\tau} \tag{18}$$

Finally, we run a UIP regression augmented with structural break indicators as well with options -implied moments.

3. Description of Options Data and Option-Implied Moments

3.1 Description Of Over-The-Counter Option Price Data

In the over-the-counter (o-t-c) currency options market, exchange rates are quoted as the domestic price of foreign currency[9]. Market quoting conventions for the pairs used in this paper are given table AT1.

We use daily o-t-c currency options data. For the purpose of extracting risk-neutral moments, there are three main advantages of using o-t-c data. First, European-style options are traded in the o-t-c market, so the option price data do not have to be adjusted for the possibility of early exercise. Second, options for a given maturity are traded each day. The third advantage is that most currency options trading takes place in the o-t-c market, so observed prices are more likely to better capture market sentiment compared to a less liquid market.

There are three important o-t-c currency market quoting conventions. First, option prices are given in terms of implied volatility instead of currency units. There is a one-to-one relationship between option price and implied volatility when using the Black-Scholes formula. Use of the Black-Scholes formula does not, however, mean traders agree with the assumptions underlying the Black-Scholes model.

Second, moneyness is measured in terms of delta instead of exercise price. The delta of an option is a measure of the responsiveness of the option's price with respect to a change in the

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[9] Thus, a fall in the exchange rate indicates an appreciation of the "domestic" currency. Also, note that the terms "domestic" and "foreign" do not have geographic significance here.

price of the underlying asset.[10] Using delta as a measure of moneyness has the advantage that when the price of an option changes, the delta does not change. The 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.

Last, option prices are quoted in combinations rather than simple call and put options. The most common option combinations are at-the-money (ATM) straddle, risk reversals (RR), and Vega-weighted butterflies (VWB).[11] An ATM straddle is the sum of a base currency call and a base currency put, both struck at-the-money. This is the most liquid structure in the o-t-c FX options market. The price of an ATM straddle can be interpreted as capturing the level of the volatility smile, and thus as capturing the general level of uncertainty regarding the distribution of future spot exchange rates.

A RR is set up when one buys a base currency call and sells a base currency put with a symmetric delta. Although the delta can be chosen to equal anything, the most liquid RR is the 25Δ, in which both the call and put have a delta of 25 percent.[12]

Finally, the VWB, which captures curvature of the volatility smile, is built by buying a symmetric delta strangle[13] and selling an ATM straddle. The 25Δ combination is the most

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[10] When using the Garman-Kohlhagen (1983) option-pricing formula, the expression for the delta of a call options is $e^{-r^f\tau}\,\Phi\left(\frac{\log\left(\frac{S_t}{K}\right)+(r^d-r^f+\frac{1}{2}\sigma)\tau}{\sigma\sqrt{\tau}}\right)$ while the delta of a put option is given by $-e^{-r^f\tau}\,\Phi\left(-\frac{\log\left(\frac{S_t}{K}\right)+(r^d-r^f+\frac{1}{2}\sigma)\tau}{\sigma\sqrt{\tau}}\right)$.

[11] These traded option combinations are sometimes interpreted as “short cut” indicators of the standard deviation, skewness and kurtosis of the distribution of future exchange rates. Their correlations with extracted risk-neutral moments can shed light on whether the two indicators capture similar information, as done in Csavas (2008). High correlations between the two indicators would suggest there isn’t much gained by using moments extracted from the whole distribution of future spot rate.

[12] That is, disregarding the sign. The delta of a put option is actually negative.

[13] A symmetric strangles combination results when one buys a call and put, with the same delta, disregarding the sign.

traded options VWB.[14] A positive value for the VWB means out-of-the-money options are on average relatively more expensive than at-the-money options. The high implied volatility of these out-of-the-money options suggests that the market perceives the underlying distribution of the spot rate to have fat tails. The price of a VWB can therefore be considered a short indicator of the kurtosis of the distribution of the future spot rate.

The definitions of these option combinations are as follows:

$$\begin{gathered}\sigma_{ATM} \;=\sigma_{0\Delta call}{=}\sigma_{50\Delta call}{+}\sigma_{50\Delta put}\\ \sigma_{25\Delta RR,\tau}=\sigma_{25\Delta c,\tau}-\sigma_{25\Delta p,\tau}\\ \sigma_{25\Delta vwb,t}=\frac{\sigma_{25\Delta c,\tau}+\sigma_{25\Delta p,\tau}}{2}-\sigma_{ATM}\end{gathered}\tag{19}$$

The sign and size of the RR volatility is related to the market's view on the skewness of the distribution of the future spot rate. To see this, note that the underlying asset is the base (foreign) currency. The payoff of a call option increases when the value of the underlying asset increases, while the value of a put option increases when the underlying asset's price goes down.[15] Therefore, a negative RR volatility indicates that the market thinks the base currency is more likely to depreciate, or, equivalently, the domestic currency is more likely to appreciate. We therefore expect negative RR volatility to be associated with a negatively skewed extracted density of the future spot rate.

The preceding discussion suggests that even the traded option combinations potentially contain useful information about the market's perception of FX risk. As noted by Csavas(2008), the ATM straddle captures perceptions about the general level of uncertainty and therefore a short-cut indicator of standard deviation. The RR captures the perceived

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[14] The Vega of a straddle is greater than the Vega of a strangle. "Vega-weighted" means the quantity of straddle has to be smaller than the quantity of the strangle.

[15] i. e. The delta of a call option is positive, while the delta of a put option is negative.

asymmetry in the distribution of future spot rates, and thus is a short-cut indicator of skewness of the distribution of the VWB captures likelihood of extreme movements, and therefore a short indicator of kurtosis. **Table 2** below shows correlations between option-implied risk neutral moments and corresponding short-cut indicators. A high correlation between the short-cut indicator and the corresponding risk-neutral moment would suggest that the two capture similar information, implying that there might be little value added by using option-implied moments instead of short-cut indicators.

[INSERT TABLE 2 HERE]

Equations (19) can be rearranged to get the implied volatilities for 0Δ call, 25Δ call and 25Δ put. Expressions for backing out implied volatilities of these "plain-vanilla" options from the prices of traded option combinations are given below:

$$\sigma_{0\Delta c,\tau} = \sigma_{ATM} = \sigma_{50\Delta c,\tau} + \sigma_{50\Delta p,\tau}$$

$$\sigma_{25\Delta c,\tau} = \sigma_{ATM} + \sigma_{25\Delta vwb,\tau} + \frac{1}{2}\sigma_{25\Delta RR,\tau} \tag{20}$$

$$\sigma_{25\Delta p,\tau} = \sigma_{ATM} + \sigma_{25\Delta vwb,\tau} - \frac{1}{2}\sigma_{25\Delta RR,\tau}.$$

Next, $K_{25\Delta p}$, $K_{ATM}, K_{25\Delta c}$,the exercise prices corresponding to σ_{ATM} , $\sigma_{25\Delta c,\tau}$ and $\sigma_{25\Delta p,\tau}$ can be backed out by using the expression for the delta of an option in the Black-Scholes world. For example, to get K_{ATM}, the strike price corresponding to σ_{ATM}, we use the fact that the ATM straddle has a delta of zero, which means K_{ATM} must therefore satisfy the condition:

$$e^{-r^f\tau}\,\Phi\left(\frac{\log\left(\frac{S_t}{K_{ATM}}\right)+\left(r^d-r^f+\frac{1}{2}\sigma_{ATM}^2\right)\tau}{\sigma_{ATM}\sqrt{\tau}}\right) - e^{-r^f\tau}\,\Phi\left(-\frac{\log\left(\frac{S_t}{K_{ATM}}\right)+\left(r^d-r^f+\frac{1}{2}\sigma_{ATM}^2\right)\tau}{\sigma_{ATM}\sqrt{\tau}}\right) = 0, \tag{21}$$

where

- r^f is the "foreign" risk-free interest rate

- S_t is the spot rate, measured in units domestic currency per unit of foreign currency.
- $\Phi(.)$ is the standard normal cumulative density function(cdf)

Recalling that Φ is a cdf, and therefore a monotone function, we can solve the equation above for K_{ATM} to get:

$$K_{ATM} = S_t e^{\left[(r^d - r^f + \frac{1}{2}\sigma^2_{ATM})\tau\right]} = F_t^{t+\tau} e^{\frac{1}{2}\sigma^2_{ATM}\tau} \qquad (22)$$

Similarly, $K_{25\Delta c}$ should satisfy the relationship:

$$e^{-r^f\tau}\,\Phi\left(\frac{\log\left(\frac{S_t}{K_{25\Delta c}}\right) + (r^d - r^f + \frac{1}{2}\sigma^2_{25\Delta c})\tau}{\sigma_{25\Delta c}\sqrt{\tau}}\right) = 0.25, \qquad (23)$$

while $K_{25\Delta p}$ should be such that

$$-e^{-r^f\tau}\,\Phi\left(-\frac{\log\left(\frac{S_t}{K_{25\Delta p}}\right) + (r^d - r^f + \frac{1}{2}\sigma^2_{25\Delta p})\tau}{\sigma_{25\Delta p}\sqrt{\tau}}\right) = -0.25. \qquad (24)$$

Rearranging equations (23) and (24) yields the following expressions for $K_{25\Delta c}$ and $K_{25\Delta p}$:

$$\begin{aligned} K_{25\Delta c} &= S_t e^{\left[-\Phi^{-1}\left(\frac{1}{4}e^{r^d\tau}\right)\sigma_{25\Delta c,\tau}\sqrt{\tau} + \left(r^d - r^f + \frac{1}{2}\sigma^2_{25\Delta c}\right)\tau\right]}, \\ K_{25\Delta p} &= S_t e^{\left[\Phi^{-1}\left(\frac{1}{4}e^{r^d\tau}\right)\sigma_{25\Delta p,\tau}\sqrt{\tau} + \left(r^d - r^f + \frac{1}{2}\sigma^2_{25\Delta p}\right)\tau\right]}. \end{aligned} \qquad (25)$$

Castagna and Mercurio (2005) point out that for tenors up to two years, the following relationship holds: $K_{25\Delta p} < K_{ATM} < K_{25\Delta c}$.

Our options data consists of daily option prices for 25Δ RR, 25Δ VWB and ATM straddles, covering the period 1 January 2007 to April 19 2011. The data cover 5 currency pairs, all involving the USD, and were obtained from a major FX options trader. Table 1 below shows how the data options data look like for a given day:

[INSERT TABLE 1 HERE].

The risk-free interest rate data are 11 am fixings of LIBOR, obtained from DataStream.

3.2 Description of Extracted Option-Implied Moments

Table AT2 contains summary statistics of extracted risk neutral moments.
Figures AF1 show the time series dynamics for each of the extracted moments. These plots show that these options-implied moments are very persistent.

Table 2 contains the correlations between the extracted options-implied moments and their corresponding short-cut indicators. We see that the correlation between options-implied standard deviation and the price of traded straddle are especially highly positively correlated. This is not necessarily the case for options-implied skewness and kurtosis and their corresponding short-cut indicators. The comovement between options-implied and corresponding is also illustrated in the time series plots in Figures AF1.

3.2.1 Unit Root Tests

The extracted moments are very persistent, as seen from the time series plots of the extracted moments given in **Figure 1** and the autocorrelations given in table AT2. Phillips-Perron unit root tests suggest that most of the series do not have unit roots, but the null of a unit root is not rejected for a number of the standard deviation series. Since Perron (1989), it is well known that in the presence of structural breaks, traditional unit root tests such as the Augmented Dickey-Fuller (ADF) test and the Phillip-Perron test are biased towards non-rejection of the null hypothesis of a unit root. Considering time series plots which do not suggest any presence of a unit root, we also conduct the Zivot-Andrews (1992) unit root test, which allows for the existence of one structural break in either the mean or the trend of the series at an unknown breakpoint. Results of unit Zivot-Andrews root tests, shown in the **Table 3**, suggest that allowing for a structural break in each of the series leads to a rejection of the null hypothesis of a unit root for almost all the series[16]. Based on the results of the Zivot-Andrews unit root tests, we treat all the series as stationary for the rest of the analysis.

[INSERT TABLE 3 HERE]

3.2.2 OLS In The Presence Of Parameter Instability.

We use the methodology of Bai and Perron (1998, 2003) to estimate break dates and then estimate linear regression models with dummy variables. For each currency pair and tenor, our final smile regression specification is of the form:

$$\begin{gathered}(f_t^{t+h} - s_{t+1}) = \alpha_{0,\tau} + \alpha_{1,\tau} * D1 + \beta_{0,\tau} * STDEV_{t,\tau} + \beta_{1,\tau} * D1 * STDEV_{t,\tau} + \gamma_{0,\tau} * \\ SKEW_{t,\tau} + \gamma_{1,\tau} * D1 * SKEW_{t,\tau} + \theta_{0,\tau} * \mathrm{KURT}_{t,\tau} + \theta_{1,\tau} * \mathrm{D1} * \mathrm{KURT}_{t,\tau} + \varepsilon_{t+\tau}\ ,\end{gathered} \tag{26}$$

where D1 is an indicator that is equal to zero before the estimated break date and equal to 1 after the break date. We allow a maximum of one breakpoint in the regression relationship between the forward bias and option-implied risk-neutral moments. Table 4 shows the estimated break dates for each currency pair-tenor combination.

[INSERT TABLE 4 HERE]

3.2.3 Term Structure Regressions

To study information contained in the term structure of implied volatility, we run yield curve-type regressions of the form

$$\begin{gathered}(f_t^{t+\tau_1} - s_{t+\tau_1}) = \gamma_{0,\tau_1} + \gamma_{1,\tau_1} * STDEV_{t,\tau_1} + \gamma_{2,\tau_1} * SKEW_{t,\tau_1} + \gamma_{3,\tau_1} * KURT_{t,\tau_1} + \gamma_{1,\tau_2} * STDEV_{t,\tau_2} + \\ \gamma_{2,\tau_2} * SKEW_{t,\tau_2} + \gamma_{3,\tau} * KURT_{t,\tau_2} + \cdots + \varepsilon_{t+\tau_1}\end{gathered} \tag{27}$$

Clarida and Taylor(1997), Clarida, Taylor, Sarno and Valente(2003) find that although forward exchange rate is a biased predictor of future spot rate-as widely documented in the UIP literature- the term structure of forward premia still contain information that is useful for

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[16] Except for the GBPUSD 9M,12M and USDJPY 9M series, which have some serious outliers.

predicting future spot rates. Chen and Tsang (2009) find that Nelson-Siegel factors extracted from the term structure of interest rate differentials can predict exchange rate movements and explain currency excess returns.

3.2.4 Global Risk Regressions

To explore information contained in option-implied correlations, we estimate the regressions of the form:

$$f_{t,AB}^{t+\tau} - s_{t+\tau,AB} = \gamma_{0,\tau} + \gamma_{1,\tau} * STDEV_{AB,t,\tau} + \gamma_{2,\tau} * SKEW_{AB,t,\tau} + \gamma_{3,\tau} * KURT_{AB,t,\tau} + \gamma_{1,\tau} * STDEV_{BC,t,\tau} + \gamma_{2,\tau} * SKEW_{BC,t,\tau} + \gamma_{3,\tau} * KURT_{BC,t,\tau} + \varepsilon_{t+\tau} \tag{28}$$

Lyons (1988, 1998) and Malz (1998) run regressions similar to (28), their motivation coming from a portfolio balancing model. In portfolio balance model, FX excess returns depend on the investor's degree of risk aversion, their holdings of assets denominated in different currencies, consumption of goods denominated in different currencies as well as the variance-covariance matrix of asset prices.

4. Empirical Results

4.1 Excess Returns and Risk-Neutral Moments

Table 4 shows the break dates in the OLS relationship between ex-post excess returns and options-implied moments of the same tenor, chosen using the Bai-Perron methodology .We test for breaks in the parameters of the following regression:

$$f_t^{t+\tau} - s_{t+\tau} = \gamma_{0,\tau} + \gamma_{1,\tau} * STDEV_{t,\tau} + \gamma_{2,\tau} * SKEW_{t,\tau} + \gamma_{3,\tau} * KURT_{t,\tau} + \varepsilon_{t+\tau} \tag{29}$$

Most of the breaks occur in late 2008 or early 2009. Longer maturities (at least 3 months) tend to have earlier break dates (before September 2008) than shorter tenors.

Tables 5A to 5E show results for regression specification (26), augmented to allow for one break at the dates specified in table 4. For all the tenors and currency pairs, options-implied higher order moments have joint explanatory power for subsequent excess currency returns, as evidenced by the F-statistics. Furthermore, in most cases, the coefficients on these moments pre and post break are statistically different.

Coefficient on standard deviation tends to be lower after the break. The coefficients on skewness tend to be negative (note that AUDUSD,EURUSD,GBPUSD are defined in USD per the other currency, while USDCAD and USDJPY are defined as other currency per USD.)

The adjusted R^2s tend to increase as the tenor increases, and tend to be significantly higher than those found in FX regressions. However, we need to first adjust the R^2s for the fact that we are using overlapping data, and that this tends to increase the R^2s as the tenor increases even if there is no corresponding increase in explanatory power. This is especially so when the explanatory variables are highly persistent, as this case for extracted options-implied moments, as shown by the AR (1) coefficients in table AT2, as well as the time series plots in Figure 1.

Table (6) shows the results of running regression (26) for 1 month tenor while using non-overlapping data. We pick the second trading of each month[17]. We again find that option-implied moments are still have significant explanatory power for subsequent excess returns. Also, similar to the results using overlapping data, there are differences in the coefficients pre-break and post break. The results of table (6) suggest that the results in tables 5A to 5E are not all being driven by our use overlapping data.

Tables 7A and 7B show the term structure results. For table 7A, we regress quarterly excess returns 1 month, 3 month and 12 month options-implied moments. For table 7B, we regress quarterly excess returns on the first three components of options-implied standard deviation, skewness and kurtosis from 1WK, 1M, 2M,3M,6M, and 12M tenor.

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[17] We also try the 15th day, there isn't much difference in the results.

Tables 8A and 8B show the global risk regressions. In table 8A, we extract the first three principal components of options-implied standard deviation, skewness and kurtosis for a tenor of 3M using all five currency pairs, and use the nine principal components as explanatory variables, with quarterly excess returns as the dependent variable. In table 8B, we still use the five currency pairs, but instead of using only 3M tenor, we obtain the principal components from the whole terms structure of global risk.

The results from tables 5, 6, 7 and 8 show a robust empirical result: options-implied moments consistently explain ex-post deviations from the uncovered interest parity. The results also show that the three sources of information from currency options- cross sections of prices, term structure of prices and from correlations- all contain significant explanatory power for the size of currency excess returns.

Table AT5 shows the cumulative proportion shows the cumulative proportion of the first three principal components, for each of the specifications we consider in this section.

[INSERT TABLE AT5 HERE]

In most cases, the first three components capture most of the variation, both for term structure regressions and for global regressions.

4.2 Augmented UIP regressions

In this section, we turn to the question: does augmenting the UIP regression yield coefficients of β closer to 1? The motivation for these augmented regressions is as follows: on one hand , the failure of UIP is usually attributed to time-varying risk premia and market expectation biases. On the other hand, we have extracted ex-ante measures of FX volatility, crash and tail risk, and a simple test of the time-varying risk premia explanation would test for the UIP coefficients after having addressed the omitted variable bias problem that is associated with time-varying risk premia explanations. We run four variations of UIP regressions:

i) Regular with change in exchange rate against the forward premium.

ii) Regular Regression allowing for structural break.

iii) Augmented regression but no break.

iv) Augmented regression with structural break.

We run the above four regressions for tenors of 1 month and 3 months , and the results are shown in tables 9A to 9D. The main conclusion from tables 9A and 9C is that the traditional UIP puzzle is not an issue during the period we study: for 1 month and 3 month tenor, the coefficients on the forward premium is actually closer to 1 than -1, and inclusion of options-implied higher order moments (without incorporating structural breaks in either equation) as additional explanatory variables does not significantly change the UIP slope coefficient.

Table 9B and 9D show that the UIP coefficients are very different before and after the break, and that the interaction of exchange rate changes and the higher order moments is stronger in the specification in which we allow for a structural break.

Results from the four UIP equation specification suggests that the UIP puzzle might be more than being an omitted variable story, as suggested by time-varying risk premia –based explanations. To get a better understanding of the UIP puzzle, we first need to control for the relationship between exchange rate changes and perceived FX volatility, crash and tail risk in addition to the first order moments picked up by the regular UIP regression. Furthermore, we might need to control for possible breaks in the relationships between exchange rate changes and changes in the moments of future exchange rate distributions**.** One way to understand the UIP puzzle then might be to carry out a density forecasting evaluation exercise, where it is possible to test which moments of the estimated density are responsible for the failure of options-implied risk-neutral density to forecast the physical density accurately.

5. Robustness Checks

In this section we carry out a number of robustness analyses. First, we use 10D risk reversals and VWBs in place of 25D options. Second, we carry out regressions using filtered time series of extracted moments to account for outliers. Lastly, we use a different methodology to extract options-implied moments. The main conclusion from these robustness checks is that are not being driven by the specific data we use to build the volatility smile, the methodology we use to extract options-implied moments or the existence of outliers in the time series of extracted moments.

5.1 Extracting Risk-Neutral Moments Using 10Δ Options

For 1 month and 3 month tenor, we continue to use the methodology of Bakshi, Kapadia and Madan (2003) and the Vanna-Volga method, but use 10Δ RRs and 10Δ VWBs in addition to the ATM straddle to construct a continuous volatility smile. Using 10Δ options combinations involve a trade-off, since 25Δ combinations are more actively traded than 10Δ options, but using 10Δ options to construct a continuous volatility smile means the amount of extrapolation done on the tails is less than what would be the case if we use 25Δ options.

Using arguments similar to those in section 2, one can show that the expressions for strikes corresponding to 10Δ call and 25Δ put are gives by the following expressions:

$$K_{10\Delta c} = S_t e^{\left[-\Phi^{-1}\left(\frac{1}{10}e^{r^d\tau}\right)\sigma_{10\Delta c,\tau}\sqrt{\tau}+\left(r^d-r^f+\frac{1}{2}\sigma^2_{10\Delta c}\right)\tau\right]}, \tag{30}$$

$$K_{10\Delta p} = S_t e^{\left[\Phi^{-1}\left(\frac{1}{10}e^{r^d\tau}\right)\sigma_{10\Delta p,\tau}\sqrt{\tau}+\left(r^d-r^f+\frac{1}{2}\sigma^2_{10\Delta p}\right)\tau\right]} \tag{31}$$

Fitting a continuous volatility smile and extracting options-implied proceeds exactly as described in section 2. We carry out analyses for 1 month and three months data. Break dates in the regression specification:

$$f_t^{t+\tau} - s_{t+\tau} = \gamma_{0,\tau} + \gamma_{1,\tau} * STDEV_{t,\tau} + \gamma_{2,\tau} * SKEW_{t,\tau} + \gamma_{3,\tau} * KURT_{t,\tau} + \varepsilon_{t+\tau} \tag{32}$$

are shown in Appendix table 6. The break dates using 25Δ options are similar to those obtained using

[INSERT APPENDIX TABLE 6]

Regression results are shown in table Appendix tables 6 and 7.

[INSERT APPENDIX TABLE 6 HERE]

[INSERT APPENDIX 7 HERE]

The main conclusion from the above exercise is that the results obtained in section four are robust to using a slightly different set of options combinations when constructing the volatility smile. The F-statistics and adjusted R^2 are comparable to those obtained for the same tenor when using 25Δ options.

5.2 Extracting Options-Implied Moments using the Malz method

5.3 Sub-sample Analysis

Tables in AT4 shows the smile regression results when we run separate regressions for each sub-sample, with the break being the break dates being those shown in table 4, determined by the Bai-Perron methodology.

[INSERT TABLES AT4 HERE]

The sub-sample analysis suggests that option-implied moments can explain subsequent excess returns in both sub-samples. However, explanatory power can vary considerably between two sub-samples, thus suggesting the importance of incorporating structural breaks in the regression relationship between excess returns and options-implied moments.

5.4 Regression Analysis Using Filtered Data

To make sure that our results are not driven by outliers, we also run the regression specifications in section 4 using filtered versions of the options-implied moments series. To filter the data, we use least median regressions, with a moving window of 30 observations.

The break dates are used here are the same as those used in section 4, determined using unfiltered data. Regression results are shown in Appendix tables 3 and 4.

[INSERT APPENDIX TABLE 3 HERE]

[INSERT APPENDIX TABLE 4 HERE]

The main conclusion from this above exercise is that, our results in section 4 are not being driven by the presence of outliers.

6. Discussion

This paper can potentially be extended in various directions. First, theoretical work addressing improved inference in the presence of overlapping data would help us compare the performance of our “smile regressions” across tenors, to address questions like: does the explanatory power of option-implied moments predict short horizon returns better than long horizon returns? This could, for example, be done by comparing the adjusted R^2s for regressions of different tenor. However, this comparison is not possible in our current set up because in cases where we have highly persistent regressors and one runs regressions with overlapping data, R^2s for tend to increase as the degree of overlapping increases, even though there is no increase in explanatory power. A study on “correcting” the R^2 to make them comparable across tenors would be useful.

In this paper, for 1 month tenor we use non-overlapping data as a robustness check that our results are not being driven by having overlapping data. Using non-overlapping data results in significant loss of information, especially in the crisis period we study in this paper, when expectations are rapidly changing.

Second, the coefficients in the regressions of excess returns on options-implied higher order moments are hard to interpret. For example, by just looking at the standard deviation and the kurtosis of the distribution of future spot exchange rates, it is not possible to tell which side of the currency pair is more risky. A framework that augments these regressions and make it easier to interpret the signs would be useful.

7. Conclusion

We extract option-implied and measures of FX volatility, crash and tail risk show that cross sections, term structures and correlations of these risk measures consistently explain ex-post excess returns. We then study how these options-implied risk measures to study empirical support for the time-varying risk premia explanation of the UIP puzzle.

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TABLES

Table 1: Sample Annualized Implied Volatilities (%)

AUSUSD on Jan. 24, 2007

Tenor	ATM	25D RR	25D BF	10D RR	10D BF
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	0.540
9 Month	7.051	-0.446	0.197	-0.743	0.571
12 Month	6.901	-0.426	0.187	-0.703	0.540

Note: “ATM” is at-the-money straddle, “25D RR” and “10D RR” are 25%- and 10%- delta risk reversals respectively; and “25D BF” and “10D BF” are 25%- and 10%- delta Vega-weighted butterflies respectively. See Section 2/3 for more details.

TABLE 2: Correlations b/w Risk Neutral Moments and Short-cut Indicators

Correlation (St Dev, ATM Straddle)

	1W	1M	2M	3M	6M	9M	12M
AUDUSD	0.99	0.985	0.98	0.97	0.95	0.93	0.91
EURUSD	0.99	0.99	0.99	0.98	0.96	0.96	0.95
GBPUSD	0.99	0.99	0.99	0.967	0.96	0.95	0.93
USDCAD	0.99	0.99	0.98	0.98	0.98	0.98	0.98
USDJPY		0.99	0.99	0.98	0.97	0.88	0.18

Correlation (Skew, Risk Reversal)

	1W	1 M	2M	3M	6M	9M	12M
AUDUSD	0.69	0.59	0.57	0.19	-0.20	-0.37	-0.51
EURUSD	0.88	0.52	0.54	0.29	0.11	-0.01	-0.21
GBPUSD	0.56	0.23	0.26	-0.10	-0.41	-0.26	-0.10
USDCAD	0.87	0.84	0.84	0.78	0.72	0.64	0.55
USDJPY		0.60	0.55	0.08	0.10	-0.62	0.05

Correlation (Kurt, Vega-Weighted Butterfly)

	1W	1 M	2M	3M	6M	9M	12M
AUDUSD	0.16	0.29	0.29	0.05	-0.31	-0.12	-0.45
EURUSD	0.18	0.24	0.16	0.11	-0.13	-0.39	-0.49
GBPUSD	0.40	0.40	0.37	0.05	-0.38	-0.06	-0.04
USDCAD	0.53	0.47	0.44	0.11	-0.41	-0.62	-0.72
USDJPY		0.07	0.17	0.52	-0.03	0.01	-0.01

Note: “St Dev”, “Skew”, and “Kurt” are the implied standard deviation, skewness, and kurtosis of the risk-neutral FX distribution. See Section 2/3 for definitions of ATM straddle, Risk Reversal, and Vega-Weighted Butterfly.

Table 3: Zivot-Andrews Unit Root Test (p-values)

TENOR	**1 Week**	**1 Month**	**2 Month**	**3 Month**	**6 Month**	**9Month**	**12 Month**
AUDUSD							
St Dev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skew	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kurt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ExReturn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EURUSD							
St Dev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skew	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kurt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ExReturn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GBPUSD							
St Dev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skew	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kurt	0.00	0.00	0.00	0.00	0.00	0.00	0.12
ExReturn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
USDCAD							
St Dev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skew	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kurt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ExReturn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
USDJPY							
St Dev.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skew	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kurt	0.00	0.00	0.00	0.00	0.00	0.07	0.41
ExReturn	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: “St Dev”, “Skew”, and “Kurt” are defined as in Table 2. “Ex Return” is excess currency returns or ex post forward bias $f_t^{t+\tau} - s_{t+\tau}$ (see Section 2 for detail.). The Zivot-Andrews(1992) unit root test tests the null hypothesis of a unit root while allowing for 1 break date, with the break date chosen endogenously.

Table 4: Break Dates for Unfiltered Moments

	1 Week	1 Month	2 Month	3 Month	6 Month	9 Month	12 Month
AUDUSD	02/24/09	02/16/09	01/19/09	01/28/09	08/04/08	05/15/08	08/07/08
EURUSD	10/21/08	02/11/09	01/16/09	02/04/09	08/07/08	08/08/08	08/07/08
GBPUSD	11/11/08	10/21/08	03/17/09	10/23/08	10/20/08	08/12/08	07/25/08
USDCAD	10/21/08	10/12/07	10/15/08	02/04/09	04/03/08	08/21/08	08/04/08
USDJPY		01/07/09	12/12/08	11/24/08	04/22/08	01/11/08	N/A

Note: We use the **breakdate()** function in the R programming language, written by Zeileis, Kleiber, Kramer and Hornik (2003). The function implements the methodology of Bai and Perron (1998, 2003) for dating structural changes in linear regression models. The breakdate is chosen according to the Bayesian Information Criterion(BIC). For each currency pair and tenor (τ) combination, we impose a maximum of 1 break date in the following regression specification:

$$f_t^{t+\tau} - s_{t+\tau} = \gamma_{0,\tau} + \gamma_{1,\tau} * STDEV_{t,\tau} + \gamma_{2,\tau} * SKEW_{t,\tau} + \gamma_{3,\tau} * KURT_{t,\tau} + \varepsilon_{t+\tau} .$$

Table 5: Excess Returns and Risk Neutral Moments (Full- Sample, Unfiltered Data)

$$f_t^{t+\tau} - s_{t+\tau} = \gamma_0 + \gamma_1 * STDEV_{t,\tau} + \gamma_2 * SKEW_{t,\tau} + \gamma_3 * KURT_{t,\tau}$$

$$+ \delta_0 * D1 + \delta_1 * D1 * STDEV_{t,\tau} + \delta_2 * D1 * SKEW_{t,\tau} + \delta_3 * D1 * KURT_{t,\tau} + \varepsilon_{t+\tau}$$

5A) AUDUSD

Tenor (τ)	**1 Week**	**1 Month**	**2 Month**	**3 Month**	**6 Month**	**9 Month**	**12 Month**
C	0.0517	0.0612	0.0767	0.1224	0.8141	0.0993	-0.1827
	[0.0100]***	[0.0213]***	[0.0257]***	[0.0487]**	[0.2298]***	[0.1194]	[0.1123]
St Dev	0.4062	0.7202	0.8983	-0.2018	-5.5871	1.509	4.5463
	[0.1913]**	[0.2235]***	[0.3112]***	[0.3048]	[1.5794]***	[0.9596]	[0.6056]***
Skew	0.0181	0.0741	0.1336	0.1796	0.3291	0.2372	0.0843
	[0.0086]**	[0.0283]***	[0.0455]***	[0.0624]***	[0.0341]***	[0.0165]***	[0.0188]***
Kurt	-0.0138	-0.0072	0.0004	0.0186	0.0161	0.0255	0.0052
	[0.0024]***	[0.0068]	[0.0079]	[0.0140]	[0.0081]**	[0.0023]***	[0.0008]***
Break	-0.0449	0.0152	0.0669	0.1863	-0.4378	0.4643	0.6888
	[0.0133]***	[0.0360]	[0.0486]	[0.0696]***	[0.2396]*	[0.1351]***	[0.1423]***
Break*St Dev	-1.2347	-2.5475	-4.2211	-3.3253	2.0131	-6.0196	-6.8233
	[0.3348]***	[0.4595]***	[0.6807]***	[0.5257]***	[1.6640]	[1.0112]***	[0.7593]***
Break*Skew	-0.0201	-0.0658	-0.1088	-0.1193	-0.4717	-0.2074	-0.1483
	[0.0127]	[0.0321]**	[0.0509]**	[0.0675]*	[0.0549]***	[0.0263]***	[0.0262]***
Break*Kurt	0.0154	0.0045	-0.0027	-0.0238	-0.0459	-0.0258	-0.0417
	[0.0030]***	[0.0077]	[0.0091]	[0.0146]	[0.0111]***	[0.0023]***	[0.0026]***
# Obs.	1104	1098	1080	1058	992	924	861
Adj-R2	0.14	0.26	0.29	0.34	0.65	0.79	0.86
F-stats	7.55	8.52	9.53	15.64	29.15	160.51	188.00
P Value	0	0	0	0	0	0	0

Note:_Newey-West (NW) HAC Standard Errors and Covariance (lag truncation=5). D1 = break dates selected in Table 4, Filtering means replacing each value o of each of the series for explanatory variables with the fitted value obtained from using Least Median Regression with a window of 30. We use the R function **robreg.filter()** found in the package **robfilter** written by Fried, Schettlinger and Borrowski(2012). F-stats report Wald test of the null $\gamma_1 = \gamma_2 = \gamma_3 = \delta_1 = \delta_2 = \delta_3 = 0$. NW Standard errors (lag truncation = 5) are reported in brackets. Asterisks indicate significance at 1% (***), 5% (**), and 10% (*) level.

5B) EURUSD

Tenor (τ)	**1 Week**	**1 Month**	**2 Month**	**3 Month**	**6 Month**	**9 Month**	**12 Month**
C	-0.0109	0.0614	0.1162	0.134	0.2185	-0.1035	-0.56
	[0.0051]**	[0.0268]**	[0.0311]***	[0.0417]***	[0.0731]***	[0.0782]	[0.0825]***
St Dev	0.8102	-0.1672	-0.5525	-0.8829	-2.0482	3.6431	7.3755
	[0.3992]**	[0.3606]	[0.3291]*	[0.2345]***	[0.8967]**	[0.8227]***	[0.6752]***
Skew	0.0107	0.0876	0.1724	0.125	0.1503	0.1018	-0.0092
	[0.0046]**	[0.0197]***	[0.0257]***	[0.0204]***	[0.0184]***	[0.0131]***	[0.0203]
Kurt	0.0006	-0.0017	-0.0006	0.0046	0.0128	0.0087	0.0002
	[0.0009]	[0.0025]	[0.0025]	[0.0023]**	[0.0020]***	[0.0008]***	[0.0018]
Break	0.0147	-0.0327	-0.005	0.0857	0.0317	0.5754	0.9831
	[0.0069]**	[0.0345]	[0.0415]	[0.0587]	[0.0844]	[0.0952]***	[0.1087]***
Break*St Dev	-0.4728	0.0561	-1.3773	-1.7368	0.599	-6.2797	-8.0396
	[0.4410]	[0.6868]	[0.7048]*	[0.6529]***	[1.0092]	[0.9561]***	[0.8359]***
Break*Skew	-0.0215	-0.1235	-0.1996	-0.152	-0.1966	-0.0718	0.0408
	[0.0064]***	[0.0224]***	[0.0295]***	[0.0275]***	[0.0337]***	[0.0350]**	[0.0237]*
Break*Kurt	-0.0039	-0.0075	-0.0106	-0.0162	-0.0321	-0.0247	-0.0142
	[0.0011]***	[0.0034]**	[0.0038]***	[0.0046]***	[0.0057]***	[0.0062]***	[0.0021]***
# Obs.	1096	1084	1075	1053	988	924	858
Adj-R2	0.06	0.19	0.3	0.38	0.53	0.75	0.78
F-stats	9.22	8.58	18.56	19.68	36.19	110.28	203.12
P Value	0	0	0	0	0	0	0

Note:_Newey-West (NW) HAC Standard Errors and Covariance (lag truncation=5). D1 = break dates selected in Table 4, Filtering means replacing each value o of each of the series for explanatory variables with the fitted value obtained from using Least Median Regression with a window of 30. We use the R function robreg.filter() found in the package **robfilter** written by Fried, Schettlinger and Borrowski(2012). F-stats report Wald test of the null $\gamma_1 = \gamma_2 = \gamma_3 = \delta_1 = \delta_2 = \delta_3 = 0.$ NW Standard errors (lag truncation = 5) are reported in brackets. Asterisks indicate significance at 1% (***), 5% (**), and 10% (*) level.

5C) GBPUSD

Tenor (τ)	**1 Week**	**1 Month**	**2 Month**	**3 Month**	**6 Month**	**9 Month**	**12 Month**
C	-0.0229	-0.0585	0.0365	-0.1052	0.0614	-0.2611	-0.1104
	[0.0062]***	[0.0221]***	[0.0130]***	[0.0368]***	[0.0869]	[0.0459]***	[0.0229]***
St Dev	1.0907	2.7294	1.1566	3.7442	2.3849	6.912	4.0239
	[0.4012]***	[0.4609]***	[0.2792]***	[0.4595]***	[0.9436]**	[0.7768]***	[0.2825]***
Skew	0.0081	0.0408	0.0772	0.0542	0.0817	-0.006	-0.0003
	[0.0065]	[0.0168]**	[0.0314]**	[0.0226]**	[0.0233]***	[0.0027]**	[0.0001]**
Kurt	0.0034	0.0062	-0.0041	0.0067	0.0041	0	0
	[0.0008]***	[0.0018]***	[0.0030]	[0.0013]***	[0.0010]***	[0.0000]*	[0.0000]**
Break	0.0294	0.0383	0.1133	-0.0176	0.0026	0.6526	0.5578
	[0.0085]***	[0.0306]	[0.0431]***	[0.0418]	[0.0969]	[0.0700]***	[0.0644]***
Break*St Dev	-0.8829	-1.8681	-1.3266	-1.2067	-1.77	-8.4819	-6.072
	[0.4927]*	[0.4958]***	[0.9269]	[0.5623]**	[1.0567]*	[0.8701]***	[0.4107]***
Break*Skew	-0.0068	-0.0472	-0.0784	-0.085	-0.0581	0.0663	0.0339
	[0.0100]	[0.0241]*	[0.0372]**	[0.0290]***	[0.0314]*	[0.0153]***	[0.0229]
Break*Kurt	-0.006	-0.0122	-0.0345	-0.0217	-0.0202	-0.0163	-0.0058
	[0.0014]***	[0.0025]***	[0.0114]***	[0.0037]***	[0.0038]***	[0.0026]***	[0.0030]*
# Obs.	1117	1100	1079	1058	992	920	852
Adj-R2	0.09	0.28	0.34	0.49	0.6	0.75	0.72
F-stats	5.05	15.14	9.92	32.38	26.65	66.54	90.06
P Value	0	0	0	0	0	0	0

Note:_Newey-West (NW) HAC Standard Errors and Covariance (lag truncation=5). D1 = break dates selected in Table 4, Filtering means replacing each value o of each of the series for explanatory variables with the fitted value obtained from using Least Median Regression with a window of 30. We use the R function robreg.filter() found in the package **robfilter** written by Fried, Schettlinger and Borrowski(2012).F-stats report Wald test of the null $\gamma_1 = \gamma_2 = \gamma_3 = \delta_1 = \delta_2 = \delta_3 = 0$. NW Standard errors (lag truncation = 5) are reported in brackets. Asterisks indicate significance at 1% (***), 5% (**), and 10% (*) level.

5D) USDCAD

Tenor (τ)	1 Week	1 Month	2 Month	3 Month	6 Month	9 Month	12 Month
C	0.0236	-0.4837	-0.0744	-0.2103	0.4174	0.2271	0.8497
	[0.0111]**	[0.1115]***	[0.0544]	[0.0514]***	[0.0628]***	[0.1944]	[0.0702]***
St Dev	-1.4618	5.2112	1.0794	1.1221	-4.8022	-6.5503	-8.258
	[0.5696]**	[0.7409]***	[1.3691]	[0.5585]**	[0.6222]***	[1.3511]***	[0.5392]***
Skew	0.0008	0.0936	-0.1942	-0.151	0.0377	-0.0009	0.036
	[0.0100]	[0.0354]***	[0.0512]***	[0.0393]***	[0.0249]	[0.0375]	[0.0106]***
Kurt	-0.0006	0.1034	-0.0097	0.0054	-0.0052	-0.0032	-0.0053
	[0.0030]	[0.0271]***	[0.0067]	[0.0092]	[0.0028]*	[0.0036]	[0.0014]***
Break	-0.0336	0.4714	0.1105	0.1135	-0.8925	-0.8064	-1.1638
	[0.0134]**	[0.1120]***	[0.0559]**	[0.0566]**	[0.0699]***	[0.1578]***	[0.1009]***
Break*St Dev	1.0306	-5.3553	-2.3061	-0.4866	8.0965	8.3834	9.5999
	[0.6047]*	[0.7804]***	[1.4068]	[0.6360]	[0.6942]***	[1.3786]***	[0.6348]***
Break*Skew	0.0015	-0.0566	0.1614	0.1326	0.1046	0.0399	-0.061
	[0.0123]	[0.0368]	[0.0527]***	[0.0405]***	[0.0291]***	[0.0407]	[0.0155]***
Break*Kurt	0.0059	-0.0996	0.018	0.0123	0.0399	0.036	0.0193
	[0.0035]*	[0.0272]***	[0.0069]***	[0.0094]	[0.0073]***	[0.0068]***	[0.0043]***
# Obs.	1105	1086	1074	1052	982	915	861
Adj-R2	0.12	0.18	0.31	0.47	0.72	0.77	0.85
F-stats	3.51	14.88	12.54	33.56	26.65	80.61	115.79
P Value	0.0019	0	0	0	0	0	0

Note:_Newey-West (NW) HAC Standard Errors and Covariance (lag truncation=5). D1 = break dates selected in Table 4, Filtered = Filtering means replacing each value o of each of the series for explanatory variables with the fitted value obtained from using Least Median Regression with a window of 30. We use the R function robreg.filter() found in the package **robfilter** written by Fried, Schettlinger and Borrowski(2012). F-stats report Wald test of the null $\gamma_1 = \gamma_2 = \gamma_3 = \delta_1 = \delta_2 = \delta_3 = 0$. NW Standard errors (lag truncation = 5) are reported in brackets. Asterisks indicate significance at 1% (***), 5% (**), and 10% (*) level.

5E) USDJPY

Tenor (τ)	1 Month	2 Month	3 Month	6 Month	9 Month	12 Month
C	-0.0131	-0.0453	-0.0419	0.057	0.1268	0.1179
	[0.0138]	[0.0136]***	[0.0189]**	[0.0255]**	[0.0203]***	[0.0109]***
St Dev	0.3431	1.0322	0.4585	-0.9596	-1.5629	0.1165
	[0.2098]	[0.2896]***	[0.2486]*	[0.2257]***	[0.2844]***	[0.1008]
Skew	-0.0047	-0.0017	-0.0335	-0.0259	-0.0157	0.0178
	[0.0168]	[0.0114]	[0.0143]**	[0.0154]*	[0.0080]**	[0.0019]***
Kurt	0.0013	0.006	0.002	0.0009	0.0004	-0.0001
	[0.0007]*	[0.0015]***	[0.0004]***	[0.0005]*	[0.0002]**	[0.0000]***
Break	0.1238	0.214	0.2392	0.2432	0.1611	
	[0.0300]***	[0.0306]***	[0.0340]***	[0.0395]***	[0.0274]***	
Break*St Dev	-2.2381	-4.5792	-2.5974	-0.9299	0.4751	
	[0.5290]***	[0.7049]***	[0.4342]***	[0.3319]***	[0.3287]	
Break*Skew	-0.0178	-0.0545	0.0083	0.0087	0.1071	
	[0.0207]	[0.0196]***	[0.0210]	[0.0250]	[0.0146]***	
Break*Kurt	-0.0115	-0.0174	-0.0123	-0.0159	0.0042	
	[0.0034]***	[0.0025]***	[0.0020]***	[0.0040]***	[0.0018]**	
# Obs.	1098	1079	1057	992	920	861
Adj-R2	0.12	0.21	0.19	0.42	0.55	0.31
F-stats	3.78	10.49	11.17	17.94	64.77	44.05
P Value	0.001	0	0	0	0	0

Note:_Newey-West (NW) HAC Standard Errors and Covariance (lag truncation=5). D1 = break dates selected in Table 4, Filtering means replacing each value o of each of the series for explanatory variables with the fitted value obtained from using Least Median Regression with a window of 30. We use the R function robreg.filter() found in the package **robfilter** written by Fried, Schettlinger and Borrowski(2012) .F-stats report Wald test of the null $\gamma_1 = \gamma_2 = \gamma_3 = \delta_1 = \delta_2 = \delta_3 = 0$. NW Standard errors (lag truncation = 5) are reported in brackets. Asterisks indicate significance at 1% (***), 5% (**), and 10% (*) level.

Table 6: One-Month Excess Returns and Risk Neutral Moments (Non-Overlapping Data)

$$f_t^{t+\tau} - s_{t+\tau} \;=\; \gamma_0 + \;\gamma_1 * STDEV_{t,\tau} + \gamma_2 * SKEW_{t,\tau} + \gamma_3 * KURT_{t,\tau}$$

$$+\;\delta_0 * D1 + \delta_1 * D1 * STDEV_{t,\tau} + \delta_2 * D1 * SKEW_{t,\tau} + \delta_3 * D1 * KURT_{t,\tau} + \varepsilon_{t+\tau}$$

FX	AUDUSD	EURUSD	GBPUSD	USDCAD	USDJPY
C	0.1595	0.087	-0.0676	-1.1367	-0.0208
	[0.0382]***	[0.0746]	[0.0241]***	[0.1164]***	[0.0556]
St Dev	1.4816	0.264	2.7121	9.6125	0.6399
	[0.1883]***	[0.3438]	[0.5195]***	[0.6839]***	[0.4725]
Skew	0.0266	0.0713	0.0523	0.2162	-0.0171
	[0.0554]	[0.0420]*	[0.0483]	[0.0266]***	[0.0425]
Kurt	-0.0436	-0.011	0.01	0.2502	-0.0017
	[0.0103]***	[0.0108]	[0.0053]*	[0.0283]***	[0.0102]
Break	-0.0511	-0.0458	0.0638	1.1344	0.2033
	[0.0806]	[0.0816]	[0.0280]**	[0.1169]***	[0.0708]***
Break*St Dev	-3.6467	0.1621	-1.392	-10.105	-3.0348
	[0.8496]***	[1.4251]	[0.5061]***	[0.7451]***	[1.1497]**
Break*Skew	-0.0062	-0.128	-0.0627	-0.1728	0.0166
	[0.0595]	[0.0527]**	[0.0664]	[0.0307]***	[0.0485]
Break*Kurt	0.0384	-0.0071	-0.0218	-0.2457	-0.0184
	[0.0132]***	[0.0124]	[0.0076]***	[0.0288]***	[0.0111]
# Obs.	51	50	51	51	50
Adj-R2	0.36	0.10	0.18	0.14	0.14
F-stats	23.7197	4.2142	6.8460	37.8234	5.6195
P Value	0.0000	0.0021	0.0000	0.0000	0.0002

Note: Monthly data using the 2nd trading day of each month. Newey-West (NW) HAC Standard Errors and Covariance (lag truncation=5). D1 = break dates selected in Table 4, Filtering means replacing each value o of each of the series for explanatory variables with the fitted value obtained from using Least Median Regression with a window of 30. We use the R function robreg.filter() found in the package **robfilter** written by Fried, Schettlinger and Borrowski(2012). F-stats report Wald test of the null $\gamma_1 = \gamma_2 = \gamma_3 = \delta_1 = \delta_2 = \delta_3 = 0$. NW Standard errors (lag truncation = 5) are reported in brackets. Asterisks indicate significance at 1% (***), 5% (**), and 10% (*) level.

Table 7: Term Structure Analysis for Quarterly Excess Returns

Dependent Variable: Quarterly Excess Return

7A) 1M, 3M, and 12M Risk Neutral Moments as Regressors

FX	**AUDUSD**	**EURUSD**	**GBPUSD**	**USDCAD**	**USDJPY**
C	0.227	0.0455	0.096	-0.0846	-0.0626
	[0.1077]**	[0.0525]	[0.0324]***	[0.0599]	[0.0384]
1M-St Dev	0.9738	2.5441	3.8378	-10.7912	7.7894
	[2.5148]	[2.1677]	[1.3911]***	[2.1432]***	[1.3731]***
1M- Skew	-0.3102	-0.3489	-0.1142	-0.0196	0.0094
	[0.0581]***	[0.0447]***	[0.0483]**	[0.1037]	[0.0217]
1M-Kurt	-0.0138	-0.0304	-0.0214	-0.0235	-0.0175
	[0.0147]	[0.0125]**	[0.0088]**	[0.0114]**	[0.0156]
3M-St Dev	1.8931	-0.8199	-6.5871	9.9664	-8.3451
	[3.1360]	[2.0935]	[2.2421]***	[2.9804]***	[1.3650]***
3M- Skew	0.1045	0.3388	0.0427	0.1832	-0.0069
	[0.0691]	[0.0445]***	[0.0398]	[0.0945]*	[0.0154]
3M-Kurt	-0.0357	0.0258	0.0025	0.0285	0.0129
	[0.0177]**	[0.0082]***	[0.0083]	[0.0137]**	[0.0063]**
12M-St Dev	-1.569	-0.6632	2.1546	-1.895	2.8736
	[0.9372]*	[0.7149]	[0.7300]***	[1.0923]*	[0.3958]***
12M- Skew	0.044	-0.0694	-0.0002	-0.0857	0.0013
	[0.0260]*	[0.0082]***	[0.0001]**	[0.0217]***	[0.0042]
12M-Kurt	0.0045	-0.0048	0	-0.0029	-0.0001
	[0.0011]***	[0.0011]***	[0.0000]**	[0.0021]	[0.0000]*
# Obs.	861	840	852	845	859
Adj-R2	0.38	0.46	0.26	0.32	0.33
F-stats	12.90	23.01	8.28	10.39	14.70
P Value	0	0	0	0	0

Note: 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 risk-neutral moments are zero.

7B) Principal Components as Regressors

FX	AUDUSD	EURUSD	GBPUSD	USDCAD	USDJPY
C	-0.0134	0.0041	-0.0074	0.0074	-0.2537
	[0.0074]*	[0.0046]	[0.0106]	[0.0049]	[0.0664]***
PC1 - St Dev	-0.0253	0.0036	0.001	0.0089	-0.0024
	[0.0067]***	[0.0035]	[0.0040]	[0.0039]**	[0.0028]
PC1 - Skew	0.0258	-0.0075	-0.0001	-0.0105	0.0074
	[0.0103]**	[0.0051]	[0.0069]	[0.0069]	[0.0019]***
PC1 - Kurt	-0.001	-0.0007	-0.0092	0.0043	-0.7724
	[0.0084]	[0.0039]	[0.0062]	[0.0087]	[0.2043]***
PC2 - St Dev	0.0635	-0.0213	0.0058	-0.0432	0.0541
	[0.0165]***	[0.0112]*	[0.0122]	[0.0073]***	[0.0081]***
PC2 - Skew	0.0798	-0.003	-0.0073	0.0291	0.0214
	[0.0164]***	[0.0060]	[0.0086]	[0.0163]*	[0.0085]**
PC2 - Kurt	0.0456	-0.0111	0.0146	0.0087	-7.7306
	[0.0080]***	[0.0115]	[0.0255]	[0.0109]	[1.8631]***
PC3 - St Dev	-0.0187	0.0557	0.1366	0.0312	0.208
	[0.0382]	[0.0238]**	[0.0566]**	[0.0318]	[0.0306]***
PC3 - Skew	0.0294	-0.0516	-0.0546	-0.062	-0.0437
	[0.0191]	[0.0134]***	[0.0162]***	[0.0201]***	[0.0132]***
PC3 - Kurt	-0.0175	-0.0391	-2.4832	0.0146	-1.7465
	[0.0256]	[0.0106]***	[0.8212]***	[0.0120]	[0.4436]***
# Obs.	849	831	851	836	853
Adj-R2	0.33	0.34	0.29	0.29	0.39
F-stats	8.65	13.98	10.30	7.95	12.69
P Value	0	0	0	0	0

Note: For each quarterly excess return, we use the first three principal components extracted from the term structure of each risk-neutral moments of that currency as regressors (see Appendix Table X for more details on these principal components.) 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 8: Global Risk Analysis for Quarterly Excess Returns

Dependent Variable: Quarterly Excess Return

8A) Principal Components of 3-Month Moments Across Currencies

FX	**AUDUSD**	**EURUSD**	**GBPUSD**	**USDCAD**	**USDJPY**
C	-0.0229	-0.0039	0.0084	0.0103	0.0187
	[0.0068]***	[0.0045]	[0.0047]*	[0.0043]**	[0.0039]***
PC1 – 3M St Dev	-0.0049	-0.001	0.0071	-0.002	-0.0017
	[0.0058]	[0.0030]	[0.0044]	[0.0041]	[0.0036]
PC1 – 3M Skew	-0.0105	0.0029	-0.0139	0.006	-0.0061
	[0.0104]	[0.0052]	[0.0079]*	[0.0076]	[0.0058]
PC1 – 3M Kurt	-0.0243	-0.0098	-0.0248	0.0157	-0.0137
	[0.0118]**	[0.0055]*	[0.0095]***	[0.0091]*	[0.0056]**
PC2 – 3M St Dev	-0.0172	-0.0198	0.0189	-0.0054	0.0139
	[0.0142]	[0.0095]**	[0.0111]*	[0.0094]	[0.0122]
PC2 – 3M Skew	-0.0275	-0.0136	-0.0138	0.0117	0.0077
	[0.0074]***	[0.0046]***	[0.0043]***	[0.0043]***	[0.0037]**
PC2 – 3M Kurt	-0.0132	-0.0099	0.005	0.0078	0.0032
	[0.0084]	[0.0043]**	[0.0049]	[0.0051]	[0.0052]
PC3 – 3M St Dev	0.0888	0.0448	0.0372	-0.0268	0.0082
	[0.0256]***	[0.0152]***	[0.0193]*	[0.0175]	[0.0138]
PC3 – 3M Skew	0.0271	0.0157	0.0173	-0.004	-0.0152
	[0.0098]***	[0.0060]***	[0.0069]**	[0.0064]	[0.0053]***
PC3 – 3M Kurt	0.035	0.0157	0.0117	-0.016	-0.0049
	[0.0127]***	[0.0059]***	[0.0081]	[0.0081]**	[0.0051]
# Obs.	1046	1046	1046	1046	1046
Adj-R2	0.26	0.19	0.21	0.18	0.14
F-stats	2.847	3.719	3.779	3.279	4.067
P Value	0.0026	0.0001	0.0001	0.0006	0

Note: 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. 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.

8B) PCA with Full Term Structure of Global Risk

FX	**AUDUSD**	**EURUSD**	**GBPUSD**	**USDCAD**	**USDJPY**
C	-0.0044	0.009	0.0206	0.0017	0.0153
	[0.0080]	[0.0046]**	[0.0060]***	[0.0054]	[0.0048]***
PC1 – all St Dev	-0.0156	-0.007	-0.0035	0.0073	-0.0022
	[0.0040]***	[0.0023]***	[0.0029]	[0.0024]***	[0.0022]
PC1 – all Skew	0.0294	0.019	0.0104	-0.0177	0.0042
	[0.0066]***	[0.0040]***	[0.0055]*	[0.0050]***	[0.0040]
PC1 – all Kurt	0.0086	0.0082	-0.002	-0.0029	-0.0044
	[0.0068]	[0.0037]**	[0.0053]	[0.0053]	[0.0033]
PC2 – all St Dev	0.0286	0.0026	0.0202	-0.0244	0.0187
	[0.0090]***	[0.0057]	[0.0087]**	[0.0061]***	[0.0061]***
PC2 – all Skew	-0.0208	-0.0147	-0.0137	0.0127	-0.0037
	[0.0033]***	[0.0021]***	[0.0027]***	[0.0025]***	[0.0025]
PC2 – all Kurt	0.0276	0.015	0.0147	-0.015	0.0015
	[0.0040]***	[0.0024]***	[0.0027]***	[0.0026]***	[0.0028]
PC3 – all St Dev	-0.022	-0.0174	-0.0077	0.0074	0.0073
	[0.0112]**	[0.0065]***	[0.0088]	[0.0076]	[0.0068]
PC3 – all Skew	-0.0232	-0.0102	-0.0083	0.0157	-0.0002
	[0.0057]***	[0.0033]***	[0.0037]**	[0.0035]***	[0.0032]
PC3 – all Kurt	0.0193	0.013	0.009	-0.0134	0.0083
	[0.0133]	[0.0075]*	[0.0097]	[0.0098]	[0.0054]
# Obs.	785	785	785	785	785
Adj-R2	0.37	0.4	0.28	0.34	0.16
F-stats	11.259	16.092	9.724	9.838	3.239
P Value	0	0	0	0	0.0007

Note: For each quarterly excess return, we use the first three principal components extracted from each moments for all tenors and all currencies as regressors (34 series per moment; see Appendix Table 5 for more details). 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 9A: Forward Premium Regressions: Monthly Data without Break

$$s_{t+1} - s_t = \alpha + \beta(f_t^{t+1} - s_t\,) + \gamma_1 * STDEV_t^{t+1} + \gamma_2 * SKEW_t^{t+1} + \gamma_3 * KURT_t^{t+1} + \varepsilon_{t+1}$$

	AUDUSD		**EURUSD**		**GBPUSD**		**USDCAD**		**USDJPY**	
C	0.0378**	-0.0496	0.0052	-0.0145	-0.0139	-0.0145	-0.0154	-0.0241	-0.0238	-0.0457
	[0.0157]	[0.0489]	[0.0113]	[0.0447]	[0.0108]	[0.0344]	[0.0105]	[0.0420]	[0.0097]**	[0.0484]
FP	1.5125***	1.5557**	1.8186***	1.7683***	0.534*	0.5786**	0.5052	0.4971	0.918	0.8071
	[0.5767]	[0.6226]	[0.3635]	[0.3359]	[0.3007]	[0.2559]	[0.3491]	[0.3628]	[0.4558]**	[0.4071]**
STDEV		-0.5053		-0.6023		-2.2884		2.4167		0.321
		[0.9453]		[1.2627]		[0.9438]**		[0.8200]***		[0.9785]
SKEW		0.0494		-0.0442		0.056		-0.0418		0.0155
		[0.0691]		[0.0432]		[0.0518]		[0.0234]*		[0.0297]
KURT		0.032		0.0043		0.0226		-0.0189		0.0042
		[0.0148]**		[0.0084]		[0.0077]***		[0.0112]*		[0.0052]
Obs	1098	1098	1084	1084	1100	1100	1086	1086	1098	1098
R2:	0.01	0.03	0.04	0.06	0.01	0.08	0	0.04	0.01	0.01

Table 9B: Forward Premium Regressions: Monthly Data with Structural Break

	AUDUSD		EURUSD		GBPUSD		USDCAD		USDJPY	
C	0.0671	-0.22	-0.0043	-0.2457	-0.0446	0.2125	-0.0869	1.9371	-0.0472	0.0448
	[0.0366]*	[0.0960]**	[0.0163]	[0.1073]**	[0.0197]**	[0.0848]**	[0.0171]***	[0.4559]***	[0.0193]**	[0.0587]
FP	10.8846	3.4444	2.1772	1.2125	-0.4692	-1.1142	0.8773	0.9307	0.1958	0.5609
	[3.6317]***	[5.1872]	[0.6756]***	[0.5480]**	[1.4661]	[0.6517]*	[1.2801]	[0.7206]	[0.8733]	[0.8527]
STDEV		-2.765***		0.6765		-10.8871		-20.85		-1.3178
		[0.9761]		[1.4392]		[1.6905]***	[2.9792]***	[0.8346]		
SKEW		-0.2488		-0.348***		-0.1768		-0.3747		0.018
		[0.1507]*		[0.0792]		[0.0673]***	[0.1432]***	[0.0676]		
KURT		0.0345		0.0069		-0.0246		-0.4142		-0.0054
		[0.0297]		[0.0102]		[0.0076]***	[0.1109]***	[0.0027]**		
D1M	0.0222	-0.0889	0.0194	0.1277	0.0502	-0.1683	0.0884	-1.8911	0.036	-0.4857
	[0.0401]	[0.1507]	[0.0224]	[0.1377]	[0.0235]**	[0.0915]*	[0.0209]***	[0.4575]***	[0.0228]	[0.1218]*
FP*D1M	-9.768	-2.7286	-0.6093	0.1188	1.0418	1.6971	-0.6156	-0.5379	0.1292	0.0877
	[3.6430]***	[5.1884]	[0.7633]	[0.6359]	[1.4826]	[0.6859]**	[1.3689]	[0.8480]	[0.9849]	[0.9361]
STDEV*D1M		10.102***		-0.1148		7.4086		21.4566		8.8566
		[1.8841]		[2.7269]		[1.8452]***	[3.1369]***	[2.1159]***		
SKEW*D1M		0.2191		0.4881***		0.2047		0.2279		0.0717
		[0.1626]		[0.0896]		[0.0971]**	[0.1487]		[0.0831]	
KURT*D1M		-0.0237		0.0293		0.0486		0.3998		0.0457
		[0.0329]		[0.0135]**		[0.0102]***	[0.1114]***	[0.0136]***		
Obs	1098	1098	1084	1084	1100	1100	1086	1086	1098	1098
R2:	0.11	0.27	0.05	0.22	0.03	0.3	0.07	0.18	0.02	0.12

Table 9C: Forward Premium Regressions: Quarterly Data without Break

$$s_{t+3} - s_t = \alpha + \beta(f_t^{t+3} - s_t\,) + \;\gamma_1 * STDEV_t^{t+3} + \gamma_2 * SKEW_t^{t+3} + \gamma_3 * KURT_t^{t+3} + \varepsilon_{t+3}$$

	AUDUSD		**EURUSD**		**GBPUSD**		**USDCAD**		**USDJPY**	
C	0.2373	-0.0891	0.0183	-0.2349	0.0157	-0.1504	-0.0415	0.1613	-0.0562	-0.1717
	[0.0703]***	[0.1857]	[0.0187]	[0.0749]***	[0.0199]	[0.0943]	[0.0190]**	[0.1207]	[0.0197]***	[0.0893]*
FP	5.7235	6.147	4.011	3.1998	3.9738	3.9929	1.9921	1.9077	1.8781	1.9384
	[2.4242]**	[2.9727]**	[0.8868]***	[0.7143]***	[0.8439]***	[0.8344]***	[0.5798]***	[0.5044]***	[0.6227]***	[0.7205]***
STDEV		4.2886		3.2699		-0.2339		1.0924		0.7076
		[1.4320]***		[1.0514]***		[1.1825]		[0.9874]		[1.0988]
SKEW		-0.0162		-0.2128		0.002		-0.0694		-0.0652
		[0.1529]		[0.0491]***		[0.0931]		[0.0433]		[0.0397]
KURT		0.0009		-0.0153		0.0258		-0.0547		0.0031
		[0.0299]		[0.0082]*		[0.0154]*		[0.0260]**		[0.0034]
Obs	1058	1058	1053	1053	1058	1058	1052	1052	1057	1057
R2:	0.07	0.14	0.09	0.18	0.15	0.24	0.02	0.1	0.03	0.05

Table 9D: Forward Premium Regressions: Quarterly Data with Structural Break

	AUDUSD		EURUSD		GBPUSD		USDCAD		USDJPY	
C	0.3467	0.5445***	0.0052	-0.5182***	0.0328	0.4605***	0.0414	0.8378***	-0.0934	0.2295**
	[0.0565]***	[0.1993]	[0.0226]	[0.1507]	[0.0390]	[0.1120]	[0.0296]	[0.2056]	[0.0716]	[0.1070]
FP	16.0635	20.1343***	6.3633***	1.7046	5.9776***	1.8838*	6.5001***	1.6307	1.3816	2.3561
	[3.3765]***	[5.1872]	[1.2602]	[0.9214]*	[1.3159]	[1.1062]	[1.6493]	[1.0196]	[1.5767]	[1.6179]
STDEV		1.7132		3.4759***		-14.6058		-4.5126		-2.2178
		[1.1879]		[0.8980]		[1.9430]***		[2.2091]**		[0.9955]**
SKEW		0.2036		-0.4795		-0.1843		0.5964		0.1274
		[0.2931]		[0.0695]***		[0.0749]**		[0.1570]***		[0.0551]**
KURT		0.006		-0.0176		-0.0252		-0.0214		-0.0076
		[0.0539]		[0.0097]*		[0.0050]***		[0.0367]		[0.0016]**
D1M	-0.0204	-1.7565***	0.0305	-0.3617	0.0046	0.0304	-0.1623***	-0.4475	0.0417	-1.0129***
	[0.0961]	[0.2783]	[0.0365]	[0.2234]	[0.0452]	[0.1365]	[0.0339]	[0.2264]**	[0.0743]	[0.1570]
FP*D1M	-12.6823	-18.748***	-5.0476***	-0.6075	-4.4995***	-0.8488	-5.8066***	-1.1833	-2.413	-1.9775
	[3.9393]***	[5.2327]	[1.3561]	[1.0250]	[1.4150]	[1.1297]	[1.6658]	[1.0531]	[1.7570]	[1.7239]
STDEV*D1M		12.2508***		7.0295***		4.465		1.8897		10.6764
		[2.0816]		[2.6068]		[2.3292]*		[2.5213]		[1.7597]**
SKEW*D1M		-0.4546		0.5865***		0.3073***		-0.5191		-0.0257
		[0.3116]		[0.1022]		[0.1045]		[0.1619]***		[0.0830]
KURT*D1M		0.0142		0.0637***		0.0853***		-0.0486		0.0486
		[0.0566]		[0.0187]		[0.0147]		[0.0374]		[0.0082]**
Obs	1058	1058	1053	1053	1058	1058	1052	1052	1057	1057
R2:	0.34	0.44	0.13	0.4	0.21	0.53	0.16	0.48	0.06	0.21

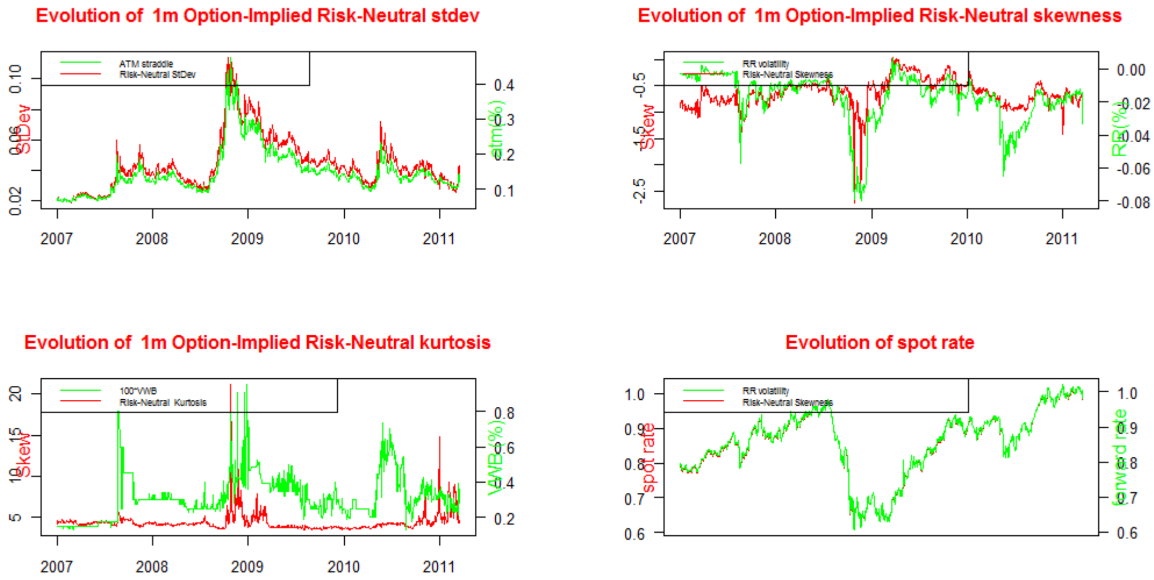
APPENDIX

A1. Glossary

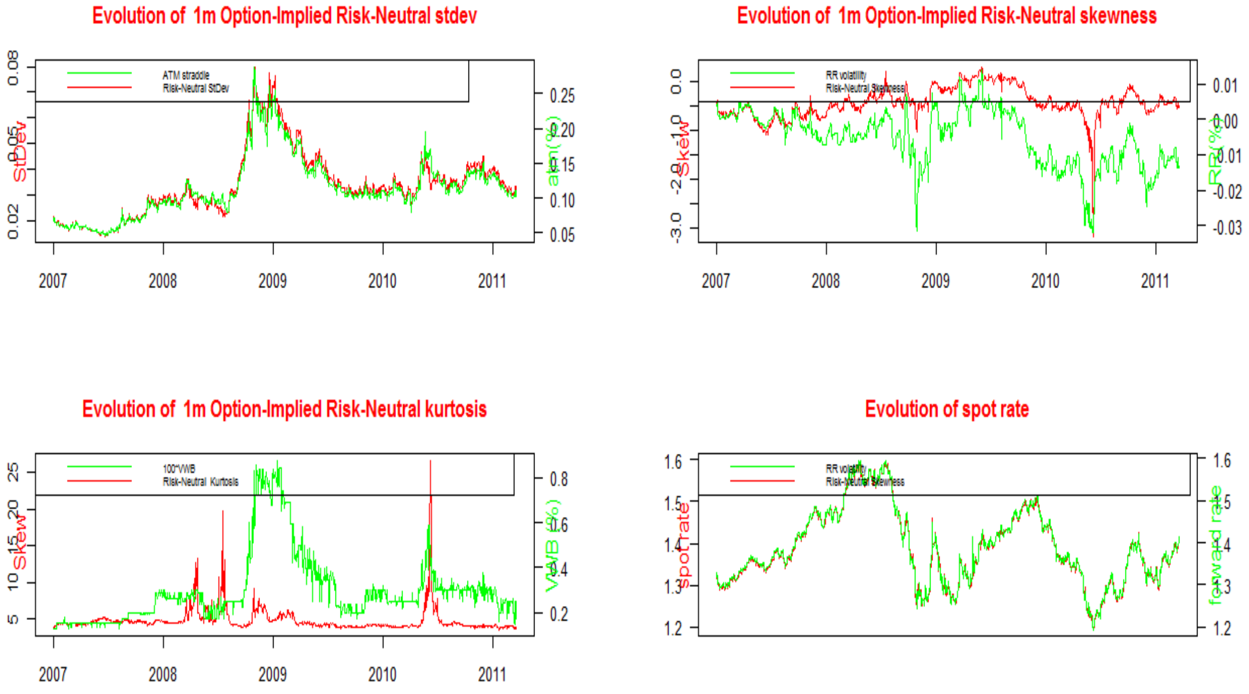
- ***Call (Put) Option***: The owner of a call (put) option has the right to buy (sell) a specific quantity of a specified asset (the underlying), at a specified price (the strike price or exercise price) on or before a specified date ("maturity"). A "European" option can only be exercised at maturity, while an "American" option can be exercised at or before maturity.
- ***Implied Volatility***: The standard deviation of the underlying asset's price that must be plugged into an option pricing formula so as to yield an option price that is equal the observed price.
- ***Delta***: The rate of change of option's price with respect to the underlying asset's price.
- ***Volatility Smile***: Plot of implied volatility of options on a given underlying asset with a given maturity against strike prices.
- ***Volatility Surface:*** volatility smile across tenure
- ***In-the- moneyness:*** An option is in the money if its pay-off at that time is greater than zero. For example, since they pay-off to a call option is max(S-K, 0), -where S is the spot rate at maturity and K the exercise price, - a call option is in the money if the spot price is greater than the exercise price.
- ***Out-of-the-moneyness:*** A call option is out of the money if the exercise price is above the spot price. A put option is out of the money if the exercise price is lower than the spot price. If an option is out of the money at maturity, then it will not be exercised.
- ***Risk-Reversal:*** A combination of a long out-of-the money call option and short equally out-of-the money put option.
- ***Strangle:*** A combination of a long out-of-the-money call option and a long equally out-of-the-money put option.
- ***Tenor:*** Time to maturity
- ***Vega:*** Rate of change of the value of an option with respect to changes in implied volatility.
- ***Volga:*** the second derivative of the option value with respect to the volatility; it measures the rate of change to vega as volatility changes
- ***Vanna :*** second order derivative of the option value, once to the underlying spot price and once to volatility
- the **Greeks** are the quantities representing the sensitivities of the price of derivatives such as options to a change in underlying parameters on which the value of an instrument or portfolio of financial instruments is dependent. They are also called the **risk sensitivities**, **risk measures** or **hedge parameters**. http://en.wikipedia.org/wiki/Greeks_(finance)

Figure 1: TIME SERIES EVOLUTIONS OF EXTRACTED RISK NEUTRAL MOMENTS: 1M , 3M, & 12M (See Online Appendix for 1WK, 2M, 6M, 9M tenors)

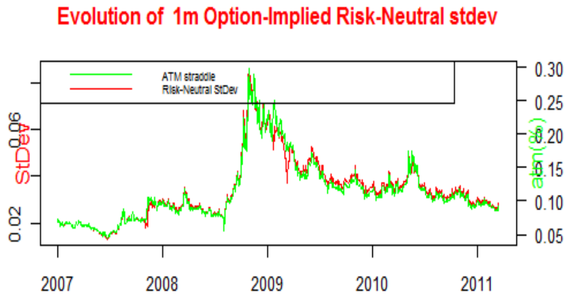
AUDUSD 1M

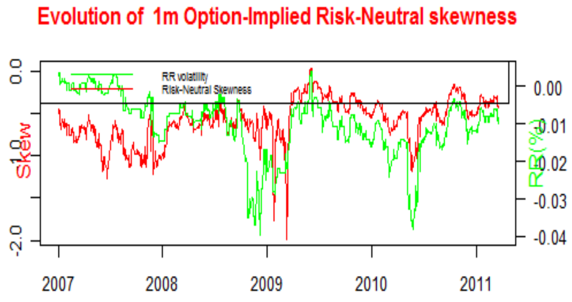


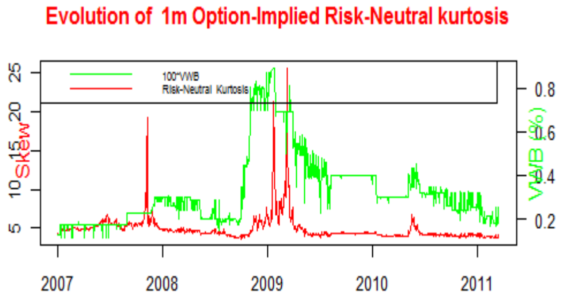
EURUSD 1M



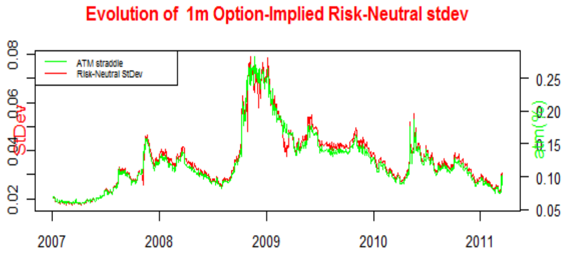
GBPUSD 1M

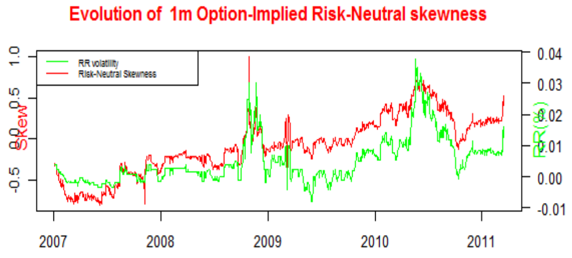


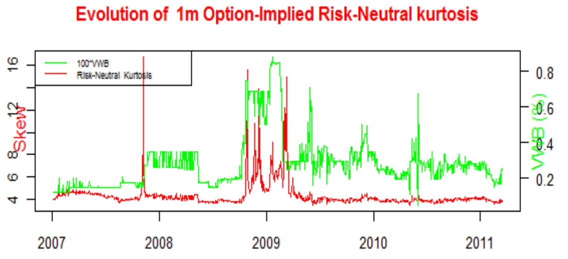


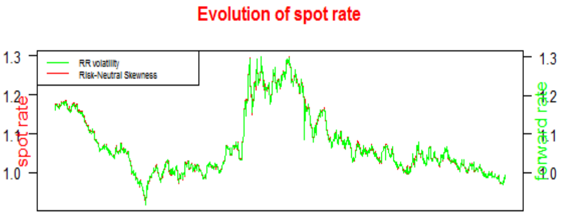


USDCAD 1M



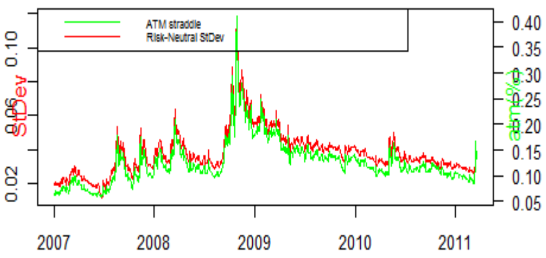




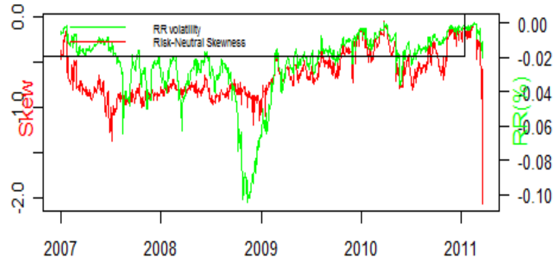


USDJPY 1M

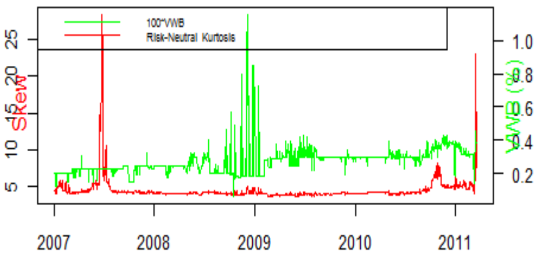
Evolution of 1m Option-Implied Risk-Neutral stdev



Evolution of 1m Option-Implied Risk-Neutral skewness



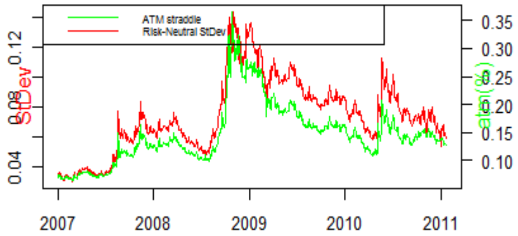
Evolution of 1m Option-Implied Risk-Neutral kurtosis



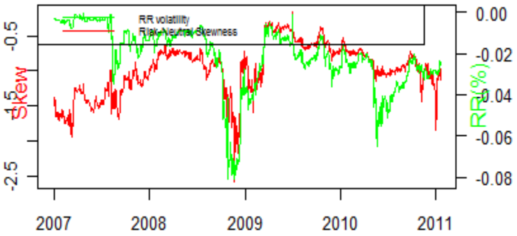
Evolution of spot rate

AUDUSD 3M

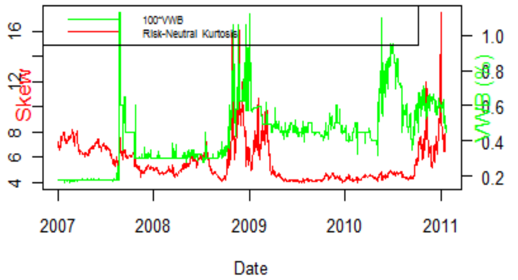
Evolution of 3m Option-Implied Risk-Neutral stdev



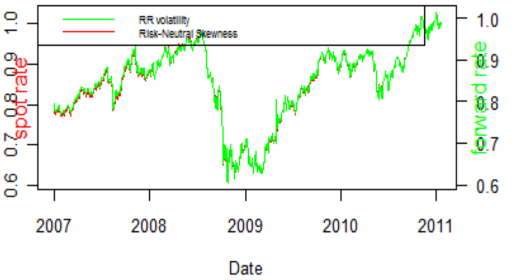
Evolution of 3m Option-Implied Risk-Neutral skewness



Evolution of 3m Option-Implied Risk-Neutral kurtosis

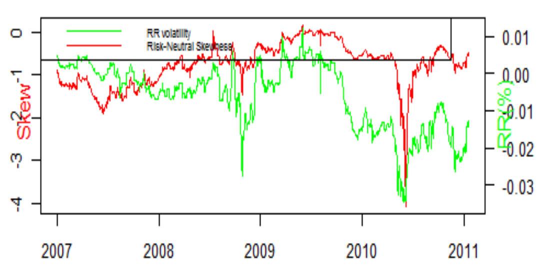


Evolution of spot rate

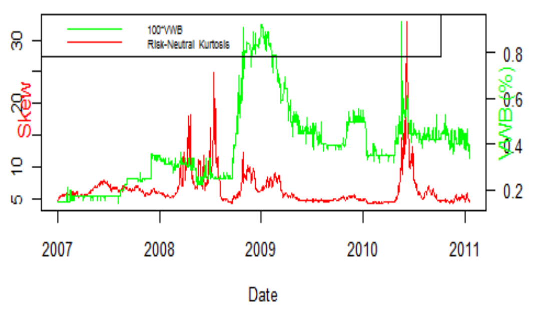


<u>EURUSD 3M</u>

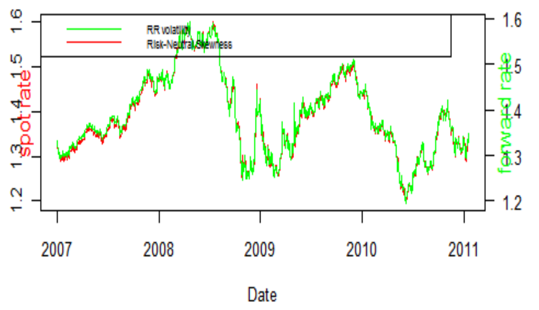
Evolution of 3m Option-Implied Risk-Neutral stdev



Evolution of 3m Option-Implied Risk-Neutral skewness

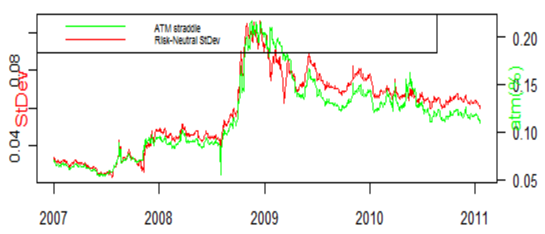


Evolution of 3m Option-Implied Risk-Neutral kurtosis

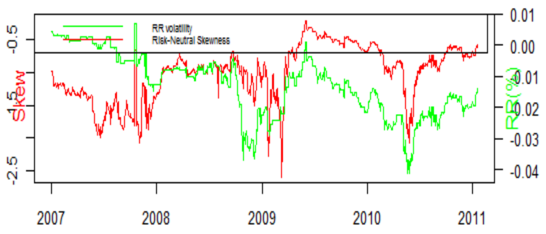


Evolution of spot rate

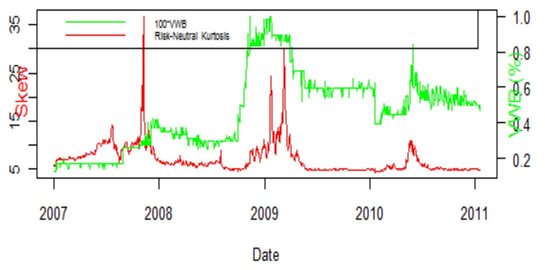
<u>GBPUSD 3M</u>



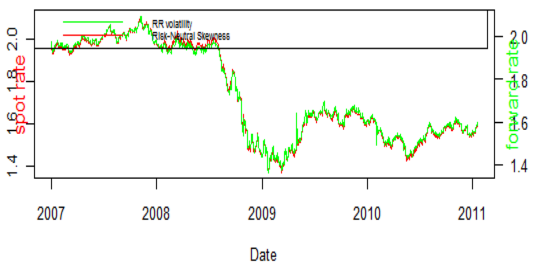
Evolution of 3m Option-Implied Risk-Neutral stdev



Evolution of 3m Option-Implied Risk-Neutral skewness

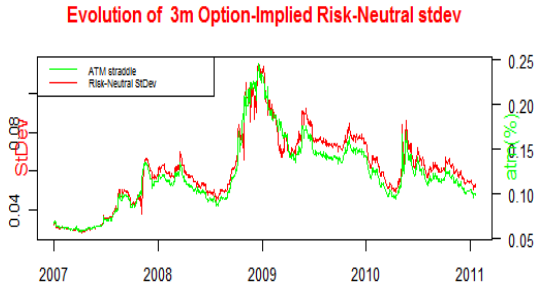


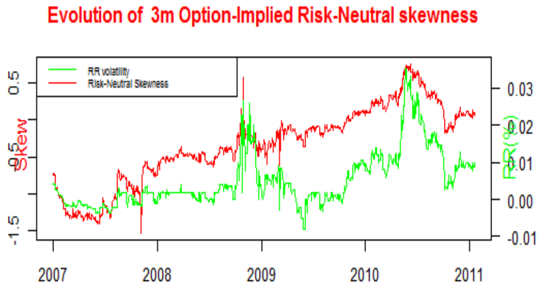
Evolution of 3m Option-Implied Risk-Neutral kurtosis

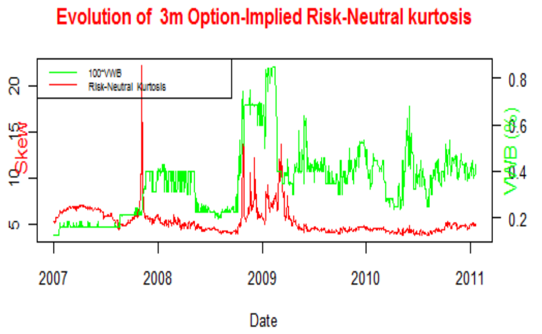


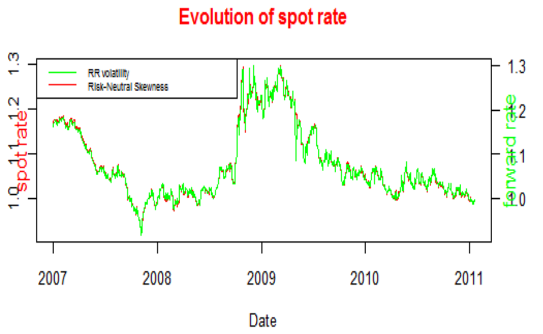
Evolution of spot rate

USDCAD 3M

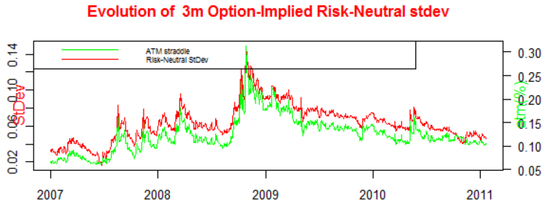

Evolution of 3m Option-Implied Risk-Neutral stdev

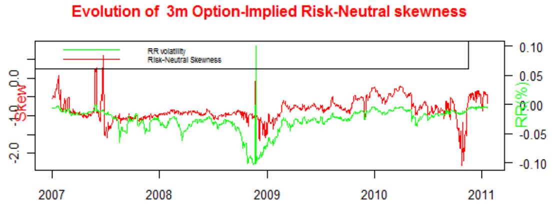

Evolution of 3m Option-Implied Risk-Neutral skewness

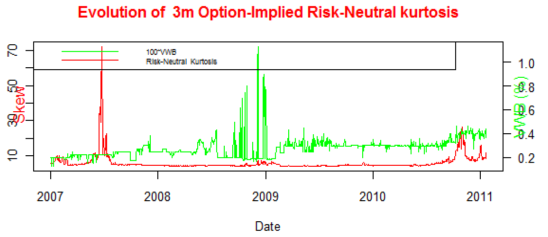

Evolution of 3m Option-Implied Risk-Neutral kurtosis

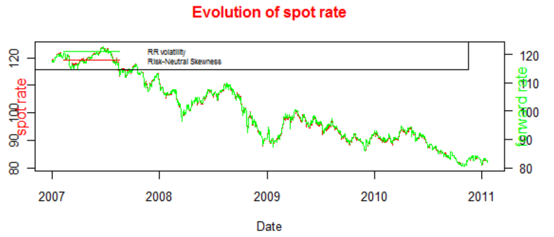

Evolution of spot rate

JPYUSD 3M

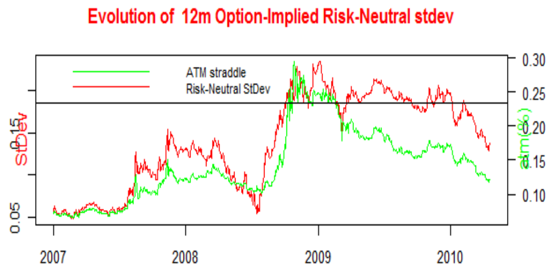

Evolution of 3m Option-Implied Risk-Neutral stdev


Evolution of 3m Option-Implied Risk-Neutral skewness


Evolution of 3m Option-Implied Risk-Neutral kurtosis


Evolution of spot rate

AUDUSD 12M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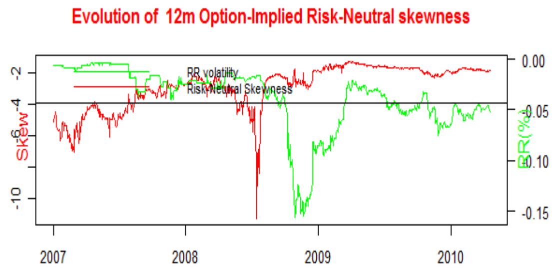
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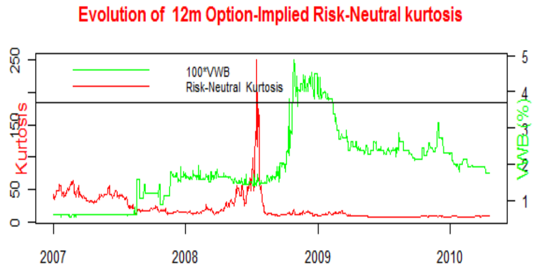
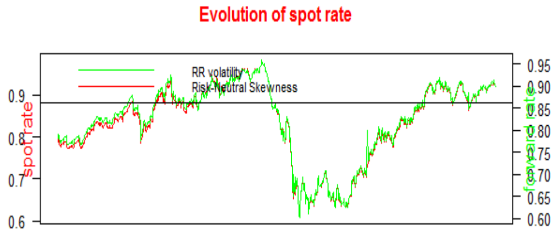
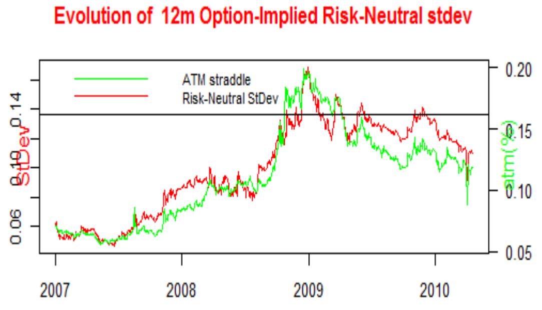
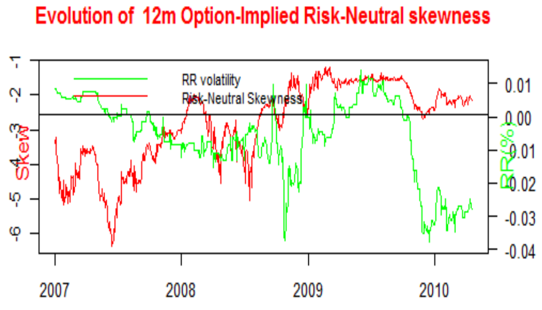

Evolution of 12m Option-Implied Risk-Neutral kurtosis


Evolution of spot rate

EURUSD 12M


Evolution of 12m Option-Implied Risk-Neutral stdev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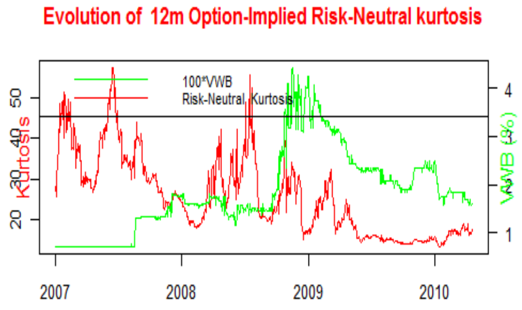
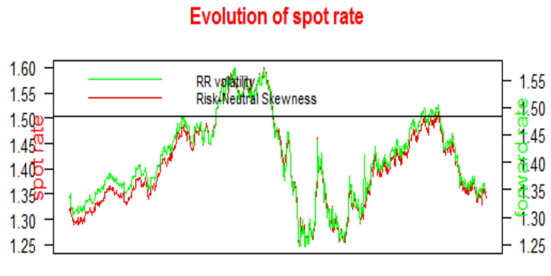
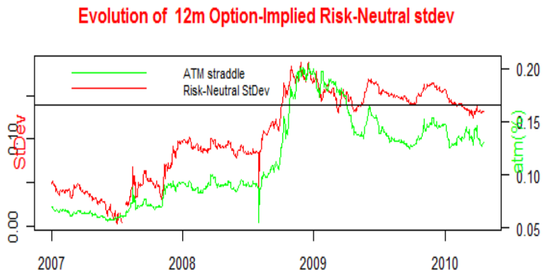
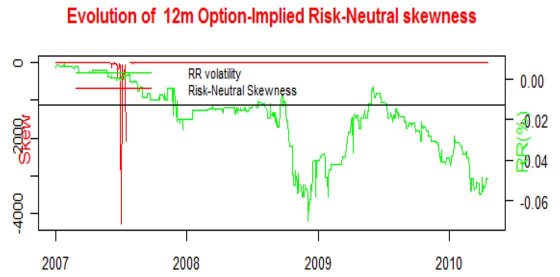
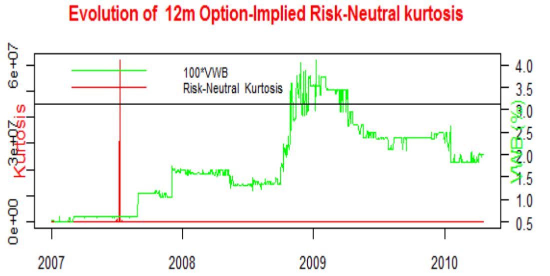

Evolution of 12m Option-Implied Risk-Neutral kurtosis

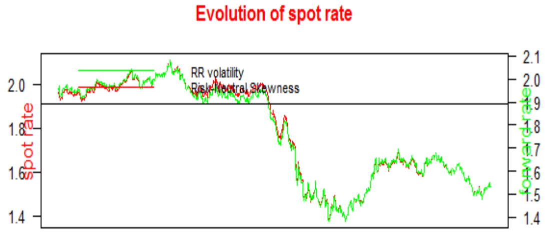

Evolution of spot rate

GBPUSD 12M

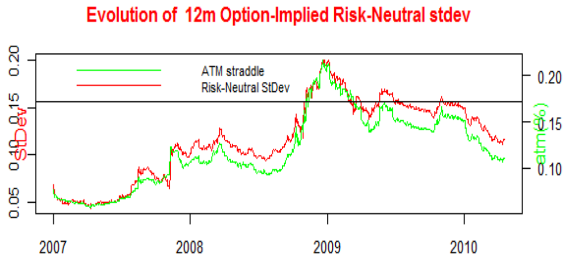


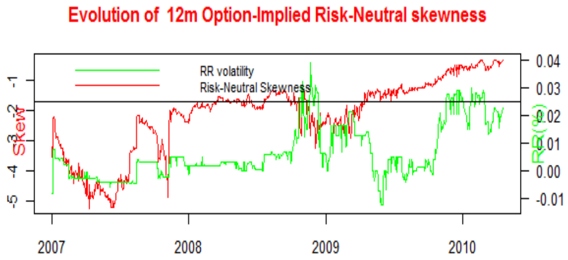


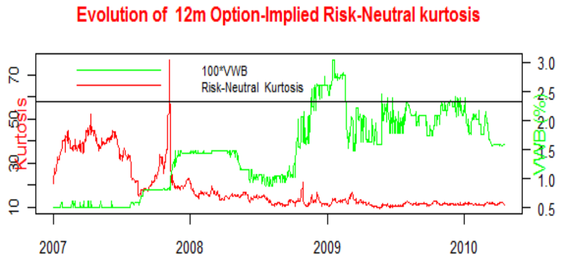


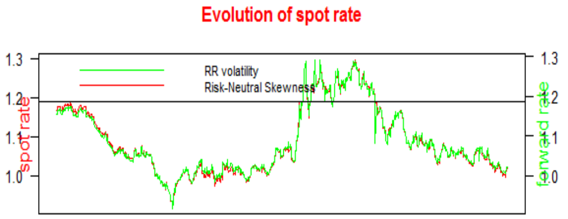


USDCAD 12M









USDJPY 12M

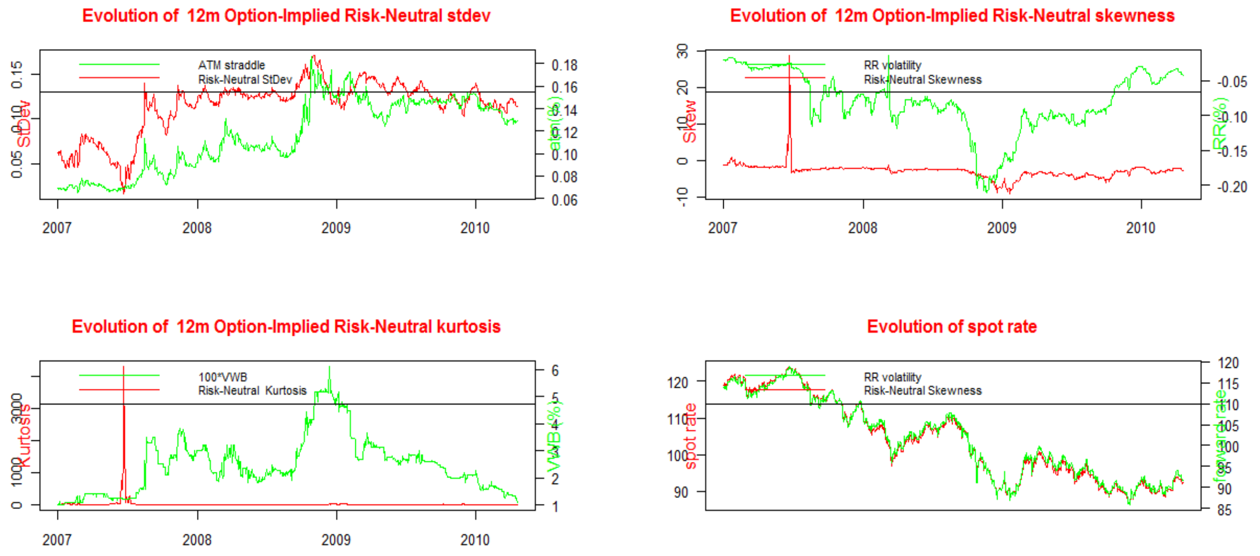


Figure 1: Time series plots of option-implied moments: 1M, 3M, & 12M tenor