The Volatility Risk Premium Embedded in Currency Options

Buen Sin Low[1] and Shaojun Zhang[2]

JEL Classification: G12, G13

Keywords: volatility risk premium, stochastic volatility, currency option, term structure of risk premium

[1]Division of Banking and Finance, Nanyang Technological University, Singapore 639798, abslow@ntu.edu.sg, phone: 65-67905753
[2]Division of Banking and Finance, Nanyang Technological University, Singapore 639798, asjzhang@ntu.edu.sg, phone: 65-67904240

We thank Phillipe Chen, Robin Grieves, William Lee, Paul Malatesta (the editor), Jun Pan, Yonggan Zhao, and the seminar participants at the Nanyang Business School, the 16th Annual Australasian Finance and Banking Conference, and the China International Conference in Finance 2004 for helpful comments and discussions. We especially thank an anonymous referee for his constructive comments and suggestions. Any remaining errors are our own responsibility. We also acknowledge financial support from the Centre for Research in Financial Services at the Nanyang Business School and the Centre for Financial Engineering at the Nanyang Technological University.

The Volatility Risk Premium Embedded in Currency Options

Abstract

This study employs a non-parametric approach to investigate the volatility risk premium in the over-the-counter currency option market. Using a large database of daily quotes on delta neutral straddle in four major currencies – the British Pound, the Euro, the Japanese Yen, and the Swiss Franc – we find that volatility risk is priced in all four currencies across different option maturities and the volatility risk premium is negative. The volatility risk premium has a term structure where the premium decreases in maturity. We also find evidence that jump risk may be priced in the currency option market.

I. Introduction

It has been widely documented in the literature that the price volatility of many financial assets follows a stochastic process. This leads to the question of whether volatility risk is priced in financial markets.

Lamoureux and Lastrapes (1993), Coval and Shumway (2001), and Bakshi and Kapadia (2003), among others, present substantial evidence that volatility risk is priced in the equity option market and that the risk premium is negative. However, although foreign currency returns have stochastic volatility (see, e.g., Taylor and Xu (1997)), there is scant evidence on the market price of volatility risk in currency option markets. In this paper, we explore the volatility risk premium in currency options.

Sarwar (2001) studies the historical prices of the Philadelphia Stock Exchange (PHLX) currency options on the U.S. Dollar/British Pound from 1993 to 1995, and reports that volatility risk is not priced for the currency options in the sample. This finding contrasts with the overwhelming evidence of the existence of volatility risk premium in the equity options markets. It is also inconsistent with other empirical findings in the currency option markets. For example, Melino and Turnbull (1990, 1995) report that stochastic volatility option models with a non-zero price of volatility risk have less pricing error and better hedging performance for currency options than do constant volatility option models. Furthermore, Black-Scholes implied volatilities for currency options have been shown to be biased forecasts of actual volatility (see Jorion (1995), Covrig and Low (2003), and Neely (2003)). One possible explanation for the bias is the presence of a volatility risk premium.

Investors are presumably risk-averse and dislike volatile states of the world. Within the framework of international asset pricing theory, Dumas and Solnik (1995) and De Santis and Gerard (1998), among others, show that foreign currency securities should compensate investors for bearing currency risk in addition to the traditional risk due to the covariance with the market portfolio. As the volatility of currency price is also uncertain, it introduces additional risk that investors have to bear and should be compensated for. Assets that lose value when volatility increases are more risky for investors to hold than those that gain value when volatility increases, such as currency options. Hence, unlike the case for foreign currency securities in the spot market, where one may expect a positive risk premium for bearing volatility risk, this may not be the case for currency options. Coval and Shumway (2001) formalize this intuition in the context of mainstream asset pricing theory and show that options have greater systematic risk than their underlying securities. They provide evidence that investors are willing to pay a premium to hold options in their portfolio as a hedge against volatile states of the world. Thus, this would make the option price higher than its price when volatility risk is not priced. In other words, the volatility risk premium in currency options would be negative if it exists.

In this paper, we investigate the volatility risk premium in the over-the-counter (OTC) currency option market.[1] We extend a new methodology proposed by Bakshi and Kapadia (2003) from equity index options to currency options and apply it to at-the-money delta neutral straddles traded in the OTC market. An at-the-money delta neutral straddle is a combination of one European call and one European put with the same maturity and strike price on the same currency. At-the-money delta neutral straddles are the most liquid option contracts traded on the OTC market. Because their prices are very sensitive to volatility, they are widely used to hedge or speculate on changes in volatility. Therefore, if volatility risk is priced in the currency option market, straddles are the best instruments through which to observe the risk premium.

Our database includes daily OTC average bid and ask implied volatility quotes for European at-the-money delta neutral straddles. The database covers the British Pound, Japanese Yen, and Swiss Franc (against the U.S. Dollar) from June 1996 to December

---

[1] The OTC currency option market is substantially more liquid than the exchange traded currency option market. The annual turnover of currency options that are traded on organized exchanges was about US$1.3 trillion in 1995 and declined to US$0.36 trillion in 2001 (see Bank for International Settlement (1997, 2003)), whereas the annual turnover on the over-the-counter market was about US$10.25 trillion in 1995 and about US$15 trillion in 2001 (see Bank for International Settlement (1996, 2002)).

2002, and the Euro from January 1999 to December 2002. In OTC currency option market, option prices are quoted in terms of volatility, expressed as a percentage per annum. For example, an option that is quoted at a 10% bid has the option premium computed by substituting 10% as the volatility figure into the Garman-Kohlhagen (1983) model, along with the prevailing current spot exchange rate and domestic and foreign interest rates.[2] One advantage of the data is that the OTC volatility quotes apply to option contracts of the same standard maturity term, regardless of which day the price is quoted. We study at-the-money straddles for maturities of 1 month, 3 months, 6 months, and 12 months. Our approach ensures that our implied volatility series are homogeneous with respect to moneyness and maturity, and that conclusions drawn from analyzing this database are unlikely to be affected by the mixture of moneyness and maturity.

Our main findings include the following.

- First, we find that volatility risk is priced in four major currencies – the British Pound, Euro, Japanese Yen, and Swiss Franc – across maturity terms between 1 month and 12 months.[3,4]
- Second, we provide direct evidence of the sign of the volatility risk premium. The risk premium is negative for all four major currencies, which suggests that

[2] In a study on the term structure of implied volatilities, Campa and Chang (1995) use equivalent OTC option volatility quotes from December 1989 to August 1992.

[3] The results are contrary to the findings of Sarwar (2001). The difference may be because Sarwar (2001) uses data for exchange-traded options, which are mixed in maturity and moneyness, whereas the quotes of OTC currency options in our study have constant maturity and apply only for at-the-money options.

[4] Evidence of volatility risk premium is also found in four other currencies against U.S. dollar and three cross currencies. The results are reported in section VI.

buyers in the OTC currency option market pay a premium to sellers as compensation for bearing the volatility risk.

- Third, and more important, we find that the volatility risk premium has a term structure in which the risk premium decreases in maturity. This study is the first to provide empirical evidence of the term structure of the volatility risk premium. Previous studies have documented that short-term volatility has higher variability than long-term volatility (e.g. Xu and Taylor (1994) and Campa and Chang (1995)), but none have investigated the implication on volatility risk premiums.
- Fourth, we document that jump risk is also priced in the OTC markets. However, the observed volatility risk premium is distinct from and not subsumed by the possible jump risk premium.

All of our findings are robust to various sensitivity analyses on risk-free interest rates, different sub-periods, and specifications of empirical models.

The paper is organized as follows. Section II details the methodology used in the study. Section III explains the unique features of OTC currency option markets and the data. Section IV describes the empirical implementation of the methodology. Section V presents our main empirical findings and Section VI reports some robustness studies. Section VII provides a summary and conclusion.

II. Methodology

Bakshi and Kapadia (2003) propose a non-parametric method to investigate volatility risk premiums in equity index option markets. Under a general stochastic option-pricing framework they prove that if volatility risk is priced in the option market, then the return of a dynamically delta-hedged call option on a stock index is mathematically related to the volatility risk premium. Hence, it is theoretically sound to infer the sign of the volatility risk premium from returns on dynamically delta-hedged call options. This approach allows the investigation of the volatility risk premium without the imposition of strong restrictions on the pricing kernel or assuming a parametric model of the volatility process.

Using this approach, Bakshi and Kapadia (2003) show that volatility risk is priced in the S&P 500 index option market and that the volatility risk premium is negative. We extend their methodology to the currency option market.

A. Theory

Assume that the spot price of a currency at time t, x_t, follows the process:

$$\frac{dx_t}{x_t} = m_t dt + \sigma_t dz_t \tag{1}$$

$$d\sigma_t = \theta_t dt + \delta_t dw_t \tag{2}$$

where z_t and w_t are standard Wiener processes, the random innovations of which have instantaneous correlation ρ. Parameters m_t and σ_t are the instantaneous drift and volatility of the currency spot price process; m_t can be a function of x_t and σ_t. The instantaneous volatility σ_t, follows another diffusion process with mean θ_t and standard deviation δ_t as specified in equation (2), where θ_t and δ_t may depend on σ_t but not on x_t.

Let f_t denote the price of a European straddle on the currency. By Ito's lemma, f_t follows the stochastic process characterized by:

(3) $$df_t = \frac{\partial f_t}{\partial x_t} dx_t + \frac{\partial f_t}{\partial \sigma_t} d\sigma_t + \left(\frac{\partial f_t}{\partial t} + \frac{1}{2}\sigma_t^2 x_t^2 \frac{\partial^2 f_t}{\partial x_t^2} + \frac{1}{2}\delta_t^2 \frac{\partial^2 f_t}{\partial \sigma_t^2} + \rho \delta_t \sigma_t x_t \frac{\partial^2 f_t}{\partial x_t \partial \sigma_t} \right) dt$$

The price change, df_t is properly interpreted mathematically as the following stochastic integral equation:

(4) $$\begin{aligned} f_{t+\tau} = {} & f_t + \int_t^{t+\tau} \frac{\partial f_u}{\partial x_u} dx_u + \int_t^{t+\tau} \frac{\partial f_u}{\partial \sigma_u} d\sigma_u \\ & + \int_t^{t+\tau} \left(\frac{\partial f_u}{\partial u} + \frac{1}{2}\sigma_u^2 x_u^2 \frac{\partial^2 f_u}{\partial x_u^2} + \frac{1}{2}\delta_u^2 \frac{\partial^2 f_u}{\partial \sigma_u^2} + \rho \delta_u \sigma_u x_u \frac{\partial^2 f_u}{\partial x_u \partial \sigma_u} \right) du \end{aligned}$$

Using standard arbitrage arguments (see Cox, Ingersoll and Ross (1985)), the straddle price, f_t, must satisfy the following partial differential equation:

(5) $$\frac{1}{2}\sigma_t^2 x_t^2 \frac{\partial^2 f_t}{\partial x_t^2} + \frac{1}{2}\delta_t^2 \frac{\partial^2 f_t}{\partial \sigma_t^2} + \rho \delta_t \sigma_t x_t \frac{\partial^2 f_t}{\partial x_t \partial \sigma_t} + (r-q)x_t \frac{\partial f_t}{\partial x_t} + (\theta_t - \lambda_t)\frac{\partial f_t}{\partial \sigma_t} + \frac{\partial f_t}{\partial t} - rf_t = 0$$

where r and q denote the domestic and foreign risk free rates. The unspecified term, λ_t, represents the market price of the risk associated with dw_t, which is commonly referred to as the volatility risk premium (see, e.g., Heston (1993)).

By rearranging equation (5) and substituting it into the last integral of equation (4), we obtain:

(6) $$f_{t+\tau} = f_t + \int_t^{t+\tau} \frac{\partial f_u}{\partial x_u} dx_u + \int_t^{t+\tau} \frac{\partial f_u}{\partial \sigma_u} d\sigma_u + \int_t^{t+\tau} \left(rf_u - (r-q)x_u \frac{\partial f_u}{\partial x_u} - (\theta_u - \lambda_u)\frac{\partial f_u}{\partial \sigma_u} \right) du$$

Substituting equation (2) into (6), we can rewrite equation (6) and the straddle price can be expressed as:

(7) $$f_{t+\tau} = f_t + \int_t^{t+\tau} \frac{\partial f_u}{\partial x_u} dx_u + \int_t^{t+\tau} \left(rf_u - (r-q)x_u \frac{\partial f_u}{\partial x_u} \right) du + \int_t^{t+\tau} \lambda_u \frac{\partial f_u}{\partial \sigma_u} du + \int_t^{t+\tau} \delta_u \frac{\partial f_u}{\partial \sigma_u} dw_u$$

We now consider a dynamically delta-hedged portfolio that consists of a long straddle position and a spot position in the underlying currency. The spot position is adjusted over the life of the straddle (t to t+τ) to hedge all risks except volatility risk. The outcome of this dynamically delta-hedged portfolio, hereafter referred to as the delta-hedged straddle profit (loss), is given by:

(8)
$$\Pi_{t,t+\tau} = f_{t+\tau} - f_t - \int_t^{t+\tau} \frac{\partial f_u}{\partial x_u} dx_u - \int_t^{t+\tau} \left(r f_u - (r-q) x_u \frac{\partial f_u}{\partial x_u} \right) du$$

From equation (7) this can also be stated as:

(9)
$$\Pi_{t,t+\tau} = \int_t^{t+\tau} \lambda_u \frac{\partial f_u}{\partial \sigma_u} du + \int_t^{t+\tau} \delta_u \frac{\partial f_u}{\partial \sigma_u} dw_u$$

The second integral in equation (9) is the Ito stochastic integral. Hence, the martingale property of the Ito integral implies:

(10)
$$E(\Pi_{t,t+\tau}) = \int_t^{t+\tau} E\left(\lambda_u \frac{\partial f_u}{\partial \sigma_u} \right) du$$

The implication of equation (10) is that if the volatility risk is not priced (i.e., λ_u = 0), then the delta-hedged straddle profit (loss) on average should be zero. If the volatility risk is priced (i.e., $\lambda_u \neq 0$), then the expected delta-hedged straddle profit (loss) on average must not be zero. Because the vega of a long straddle, $\partial f_u / \partial \sigma_u$, is positive, the sign of the volatility risk premium, λ_u, determines whether the average delta-hedged straddle profit is positive or negative.

B. Testable Implications

The theory suggests that the return on buying a straddle and dynamically delta-hedging this position until maturity is related to the volatility risk premium. Although the theory requires the assumption of continuous hedging, in practice, rebalancing takes place only at discrete times.[5] Suppose that we rebalance the delta-hedged portfolio at N equally spaced times over the life of the straddle between time t and $t+\tau$. That is, the hedging position is calculated at time t_n, n = 0, 1, 2, …. N-1, where $t_0 = t$ and $t_N = t+\tau$. We compute the delta-hedged straddle profit at the maturity $t+\tau$ by:

$$(11)\qquad \Pi_{t,t+\tau} = Max\left(x_{t+\tau} - k, k - x_{t+\tau}, 0\right) - f_t - \sum_{n=0}^{N-1}\Delta_{t_n}\left(x_{t_n} - x_{t_{n+1}}\right) - \sum_{n=0}^{N-1}\left(rf_t - (r-q)\Delta_{t_n} x_{t_n}\right)\frac{\tau}{\mathrm{N}}$$

where, f_t is the straddle premium at time t, $x_{t+\tau}$ is the currency price at the maturity $t+\tau$, k is the strike price of the straddle, Δ_{t_n} is the delta of the long straddle, r and q are the domestic and foreign interest rates. The first term on the right-hand side of the equation is the payoff of the long straddle at maturity $t+\tau$, the second term is the cost of buying the straddle at time t, the third term is the rebalancing cost, and the last term adjusts for the interest expenses on the second and third terms. The delta-hedged straddle profit (loss) allows us to test the following two hypotheses:

- *Hypothesis 1: If, on average, $\Pi_{t,\, t+\tau}$ is non-zero, then volatility risk is priced in the currency option market.*
- *Hypothesis 2: If, on average, $\Pi_{t,\, t+\tau}$ is negative (positive), then the volatility risk premium embedded in the currency option is negative (positive).*

---

[5] Bakshi and Kapadia (2003) show that the bias in the delta-hedged straddle outcome caused by discrete hedging is small relative to the effect of a volatility risk premium. Melino and Turnbull (1995) provide simulation evidence to show that the discrete delta hedging error with daily re-balancing is very small. For example, their average hedging errors, as a percentage of contract size, for a 1-year at-the-money currency option are only 0.06% and 0.31% if volatility is assumed to be constant or stochastic, respectively.

III. Description of the OTC Currency Option Market and Data

The OTC currency option market has some special features and conventions. *First*, the option prices on the OTC market are quoted in terms of deltas and implied volatilities, instead of strikes and money prices as in the organized option exchanges. At the time of settlement of a given deal, the implied volatility quotes are translated to money prices with the use of the Garman-Kohlhagen formula, which is the equivalent of the Black-Scholes formula for currency options. This arrangement is convenient for option dealers, in that they do not have to change their quotes every time the spot exchange rate moves. However, as pointed out by Campa and Chang (1998), it is important to note that this does not mean that option dealers necessarily believe that the Black-Scholes assumptions are valid. They use the formula only as a one-to-one non-linear mapping between the volatility-delta space (where the quotes are made) and the strike-premium space (in which the final specification of the deal is expressed for the settlement). *Second*, competing volatility quotes of option contracts are available on the market everyday, but only for standard maturity periods, such as 1-week, 1-, 3-, 6-month, and so on. For example, a 3-month option quote on Monday will become an odd period (3 months less 1 day) option quote on Tuesday, and competing quotes for this odd period option are not available on Tuesday. *Third*, most transactions on the market involve option combinations. The popular combinations are straddles, risk reversals, and strangles. Among these, the most liquid combination is the standard delta-neutral straddle contract, which is a combination of a call and a put option with the same strike.

The strike price is set, together with the quoted implied volatility price, so that the delta of the straddle computed on the basis of the Garman-Kohlhagen formula is zero.

As the standard straddle by design is delta-neutral on the deal date, its price is not sensitive to the market price of the underlying foreign currency. However, it is very sensitive to changes in volatility. Because of its sensitivity to volatility risk, delta-neutral straddles are widely used by participants in the OTC market to hedge and trade volatility risk. If the volatility risk is priced in the OTC market, then delta-neutral straddles are the best instruments through which to observe the risk premium. For this reason, Coval and Shumway (2001) uses delta-neutral straddles in their empirical study of expected returns on equity index options and find that volatility risk premium is priced in the equity index option market.

Our main option dataset consists of daily average bid and ask implied volatility quotes for the 1-, 3-, 6-, and 12-month delta-neutral straddles on four major currencies – the British Pound, the Euro, the Japanese Yen, and the Swiss Franc[6] – at their U.S. Dollar prices. Our sample spans a period of approximately 7.5 years, from June 3, 1996 to December 31, 2003. The 2003 data are used for calculating the delta-hedged straddle profit on the straddle bought in 2002. The data are obtained from Bloomberg, who collected them at 6 p.m. London time from large banks participating in the OTC currency option market. Other data collected are synchronized daily average bid and ask spot U.S. Dollar prices of each currency from Bloomberg. Because the British Pound, Euro,

[6] We chose to study currency options on these four currencies because they are the most liquid among all currencies. According to the Bank for International Settlement (2002), they accounted for approximately 67% of the total size of the OTC currency options traded in April 2001. As a robustness test we also study seven other less liquid currency options and the results are reported in section VI.

Japanese Yen, Swiss Franc, and U.S. Dollar Treasury bill yields that exactly match each option period are not available, the repurchase agreement interest rates (i.e., repo) for each currency, which match the option maturity period, are used.[7]

Figure 1 uses boxplots to show the distribution of the daily implied volatility quotes on 1-, 3-, 6-, and 12-month delta-neutral straddles for the four currencies between June 1996 and December 2002, except the Euro. The solid box in the middle of each boxplot represents the middle 50% of the observations ranging from the first quartile to the third quartile, and the bright line at the center indicates the median. Several patterns stand out in Figure 1. First, at all maturities, the British Pound has the lowest level of implied volatility and the smallest variation among the four currencies, whereas the Japanese Yen has the highest level of implied volatility and the greatest variability. Take the one-month maturity as an example. At one extreme, the implied volatility of the British Pound has a median of 8.3% per annum and an inter-quartile range of 2%. At the other extreme, the implied volatility of the Japanese Yen has a median of 11.2% and an inter-quartile range of 3.6%. In between, the Swiss Franc and Euro have median implied volatilities of 10.6% and 10.8%, and inter-quartile ranges of 2.4% and 3.0%.

Insert Figure 1 here

[7] The repo rate has a credit quality that is closest to the yield of a Treasury bill. However, to examine the sensitivity of our results to the use of repo rates instead of the true risk-free rates, we adjust for credit quality spread by subtracting 1% from the repo rates and use the reduced rates to rerun the empirical tests. We obtain qualitatively the same results for the British Pound, Euro, and Swiss Franc. We could not do this for the Japanese Yen because its repo rates are very close to zero.

Second, there is a term structure in the variability of the volatility quotes for all four currencies. Specifically, the variability is a decreasing function of the time-to-maturity as short-dated options have much higher variability than long-dated options. Campa and Chang (1995) observe a similar term structure in their sample of OTC volatility quotes for four major currencies in a different time period. Xu and Taylor (1994) study the term structure of implied volatility embedded in PHLX traded options on four currencies and report that long-term implied volatility has less variability than short-term implied volatility. The term structure in variability of implied volatility is consistent with a mean-reverting stochastic volatility process (see Stein (1989) and Heynen, Kemna, and Vorst (1994)). More importantly, it has an implication for the volatility risk premium. Because the variability of short-term volatility is much higher than that of long-term volatility, if option buyers were to pay a volatility risk premium, then they would pay more in short-term options. This means that the volatility risk premium should have a term structure in which the risk premium is a decreasing function of maturity. We report empirical evidence in relation to this hypothesis in Section V.

Third, the boxplots show the skewness of the implied volatility distribution. In each boxplot, the lower bracket connected by whiskers to the bottom of the middle box indicates the larger value of the minimum or the first quartile less 1.5 times the inter-quartile range, while the upper bracket connected by whiskers to the top of the middle box indicates the lower value of the maximum or the third quartile plus 1.5 times the inter-quartile range. For a right-skewed distribution, the upper bracket is further away from the box than the lower bracket; the pattern reverses for a left-skewed distribution. The lines beyond the lower or upper bracket represent outliers. The four currencies differ in skewness of implied volatility. While the British Pound and the Swiss Franc have close-to symmetric distributions, the distributions of the Euro and the Japanese Yen are clearly right skewed and the Yen has far more outliers (i.e., a much fatter tail) than the other three currencies. A close examination shows that a majority of the outliers in the Yen occurred during the Asian currency crisis in 1997 and 1998. Figure 2 shows the time series plot of the implied volatility for the 3-month at-the-money straddle for the British Pound, the Japanese Yen, and the Swiss Franc between June 1996 and December 2002. The two vertical dash lines indicate the start and the end of the Asian currency crisis. The crisis dramatically changed the price process of the Japanese Yen during that period, but had little effect on the British Pound and Swiss Franc. This suggests that we should conduct a robustness analysis for the post-crisis sub-period.

Insert Figure 2 here

IV. Empirical Implementation

Following the theory discussed in Section II, we now consider portfolios of buying delta-neutral straddles and dynamically delta-hedging our positions until maturity. We rebalance the delta-hedged portfolio daily and measure the delta-hedged straddle profit (loss) from the contract date t to the maturity date $t+\tau$, $\Pi_{t,\,t+\tau}$, by the formula

$$\Pi_{t,t+\tau} = Max\left(x_{t+\tau} - k, k - x_{t+\tau}, 0\right) - f_t - \sum_{n=0}^{N-1} \Delta_{t_n} \left(x_{t_n} - x_{t_{n+1}}\right) - \sum_{n=0}^{N-1} \left(r_t f_t - \left(r_t - q_t\right)\Delta_{t_n} x_{t_n}\right)\frac{\tau}{\mathrm{N}}$$

where k denotes the strike price of the straddle, and Δ_{t_n} is the delta of the straddle based on the Garman-Kohlhagen model,

(12) $$\Delta_{t_n} = e^{-q_t(t_n+\tau)}\left[2N(d_1)-1\right]$$

where $d_1 = \dfrac{\ln\dfrac{x_{t_n}}{k} + \left(r_t - q_t + \dfrac{1}{2}\sigma_{t_n}^2\right)(t_n+\tau)}{\sigma_{t_n}\sqrt{t_n+\tau}}$ and $N(d_1)$ is the cumulative standard normal distribution evaluated at d_1. The Garman-Kohlhagen model, as an extension of the Black-Scholes model to currency options, is a constant volatility model. Hence, the delta computed from the Garman-Kohlhagen model may differ from the delta computed from a stochastic volatility model. We mitigate this problem by adopting a modified Garman-Kohlhagen model, in which the volatility that is employed to compute the delta for daily rebalancing is updated based on the daily average bid and ask implied volatility quotes. Chesney and Scott (1989) conclude that actual prices on foreign currency options conform more closely to this modified Garman-Kohlhagen model than to a stochastic volatility model or to a constant volatility Garman-Kohlhagen model. Bakshi and Kapadia (2003) also provide a simulation exercise to show that using the Black-Scholes delta hedge ratio, instead of the stochastic volatility counterpart, has only a negligible effect on delta-hedged results. We report a robustness study in section VI that examines the impact of potential mis-measurement of the hedge ratio

More specifically, we take the following two steps to maintain the delta-hedged portfolio until the maturity. *First, we need to compute the money price for the straddle.* This is achieved by a one-to-one mapping between the volatility-delta space and the strike-premium space using the Garman-Kohlhagen model. For an observed implied volatility quote on day t, the strike price of the delta-neutral straddle is determined by the formula $k = x_t e^{(r_t - q_t + 0.5\sigma_t^2)\tau}$, where x_t denotes the synchronized spot foreign currency price on day *t*, r_t and q_t are the domestic and foreign interest rates per annum, τ is the time-to-maturity expressed in years, and σ_t is the average bid and ask implied volatility quote.[8] This strike price formula is used in the OTC market by convention. The straddle premium is then computed using the Garman-Kohlhagen model, together with the computed strike price, the synchronized spot foreign currency price, and interest rates.

Second, we form and maintain the delta-hedged portfolio until the maturity. Suppose that, on day *t*, we bought a straddle contract at the premium computed as above. As the straddle is in itself delta neutral, the delta-hedged portfolio on day *t* is composed of only the straddle. However, on the following day *t+1*, the straddle becomes an odd-period contract and may no longer be delta neutral. Hence, to maintain a delta-hedged portfolio, we need to sell the delta amount of the foreign currency against the U.S. Dollar at the day *t+1*spot price. We therefore re-compute the delta using Equation (12) with the spot price, interest rates, and the estimated volatility of an odd-period straddle contract at day *t+1*.[9] We estimate the volatility of an odd-period straddle contract using the linear total variance method (see Wilmott (1998)) to interpolate the volatility of standard maturities:

(13) $$\sigma_{T_2} = \frac{1}{\sqrt{T_2}}\left[T_1\sigma_{T_1}^2 + \left(\frac{T_2 - T_1}{T_3 - T_1}\right)\left(T_3\sigma_{T_3}^2 - T_1\sigma_{T_1}^2\right)\right]^{1/2}$$

[8] Equation (12) shows that the delta of a straddle is zero only when $d_1 = 0$. The strike price is computed in such a way that $d_1 = 0$.

[9] We cannot use the quoted volatility on day *t+1* because volatility quotes are valid only for straddles of standard maturities such as 1 month or 3 months. Volatility has to be estimated for odd-period straddles.

where $T_1 < T_2 < T_3$, σ_{T_1} and σ_{T_3} denote the average bid and ask implied volatility quotes for the standard maturities T_1 and T_3 available in the market, and σ_{T_2} is the volatility for the non-standard maturity T_2 that we need to estimate by interpolation. We also update the interest rates on a daily basis in rebalancing the delta-hedged portfolio. The foreign currency sold (bought) is borrowed (invested), and the corresponding long (short) U.S Dollar cash (net of the straddle premium incurred at time *t*) is invested (borrowed) at their respectively interest rates. We continue to rebalance the delta-hedged portfolio on a daily basis until the straddle maturity date. The net U.S. Dollar payoff is the delta-hedged straddle profit (loss).

V. Empirical Results

A. Negative Volatility Risk Premium

In this section, we document our empirical findings. Table 1 reports the statistical properties of the delta-hedged straddle returns on four currencies at four maturities. The delta-hedged straddle returns are calculated as the U.S. Dollar delta-hedged straddle profit (loss) from holding the dynamically delta-hedged portfolio until maturity, divided by the straddle contract size in U.S. Dollars. We annualize the returns to make them comparable across maturities. For each combination of currency and maturity, delta-hedged straddle returns comprise a time series of daily observations. This arises because, for each standard maturity, we buy an at-the-money delta neutral straddle each trading day and maintain a delta-hedged portfolio of the straddle and underlying currencies until the straddle matures. The first column of Table 1 lists the number of observations in each time series. The Euro has fewer observations than the other three currencies because it only came into existence in January 1999. In the second column, we report the percentage of daily straddle observations that have negative returns when we buy a straddle and maintain the delta-hedged portfolio until maturity. The percentage is much bigger than 50% in all cases, and is 85% for the British Pound at the 12-month maturity. This indicates that for most of the time, OTC straddle sellers earn positive profits by selling straddles and hedging their exposures. According to the theory in Section II, this suggests that such profits are a compensation for bearing the risk of volatility changes. The high percentage of negative delta-hedged straddle returns indicates that our results are not biased by outliers.

Insert Table 1 here

We now investigate whether delta-hedged straddle returns are statistically significant. The unconditional means and standard deviations of delta-hedged straddle returns are listed in the third and fourth columns of Table 1. The mean return is negative for all cases[10]. The high standard deviations of the returns make the means appear insignificantly different from zero. However, it is misleading to use the unconditional standard deviation to test the mean, because serial correlation in the time series of delta-

[10] We have run the empirical tests using the average bid and ask straddle prices to reduce the impact of bid ask spread if there is any. We have also run the empirical tests using both the bid prices and the ask prices. The results are qualitatively similar to those using straddle average bid and ask prices.

hedged straddle returns can cause the standard deviation to be a biased measure of actual random error. The next three columns of Table 1 show that the first three autocorrelation coefficients are quite large and decay slowly. This indicates that the time series may follow an autoregressive process. We calculate the partial autocorrelation coefficients in Table 1. The first order partial autocorrelation coefficient is large in all cases, while the second and third order autocorrelation coefficients become much smaller. The pattern exhibited in both autocorrelation coefficients and partial autocorrelation coefficients suggests fitting an autoregressive process of order 3 (i.e., AR(3)) to the time series of the delta-hedged straddle returns.[11] An AR(3) process can be represented by the following model: $y_t = \alpha + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 y_{t-3} + \varepsilon_t$, where ε_t is a white noise process. Its unconditional mean is given by the formula

$$E(y_t) = \frac{\alpha}{1 - \beta_1 - \beta_2 - \beta_3}$$

which implies that the null hypothesis of a zero unconditional mean is equivalent to the null hypothesis that the intercept of the AR(3) process is equal to zero.

We estimate parameters of the AR(3) process and report the estimated intercept and its p-value for the *t*-statistic in the last two columns of Table 1. The intercept is significantly negative in most cases for the British Pound, the Euro, and the Swiss Franc, whereas it is negative, although insignificant, for the Japanese Yen. We suspect that the non-significance of the Japanese Yen is due to the Asian currency crisis. Hence, in

[11] In an unreported analysis, we also fit AR(1) and AR(5) processes to the data and observe the same patterns.

Section VI we report a robustness analysis for the post-crisis sub-period from July 1999 to December 2002.

Relying on the general equilibrium model of Cox, Ingersoll and Ross (1985), Heston (1993) and Bates (2000), among others, suggest that the volatility risk premium is positively related to the level of volatility. To control for the level of volatility, we consider the following model for the delta-hedged straddle returns:

$$y_t = \alpha + \gamma\sigma_t + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 y_{t-3} + \varepsilon_t \tag{14}$$

where y_t is the delta-hedged straddle return, and σ_t is the implied volatility. We include three lagged variables y_{t-1}, y_{t-2}, and y_{t-3}, to control for serial correlation.

Table 2 reports the results of estimating the above model for four currencies at four maturities. The coefficient of implied volatility, γ, is negative for all currencies at all maturities. To test its significance, we use the *t*-test statistic based on Newey-West (1987) heteroskedasticity and autocorrelation consistent standard errors. The test shows that γ is significantly negative in all cases. This again provides evidence that market volatility risk is priced in the OTC currency option markets.

Insert Table 2 here

B. Effect of Overlapping Period

We obtain our daily delta-hedged straddle returns by purchasing a straddle and maintaining a delta-neutral portfolio using the spot currency market until the straddle matures. In calculating the delta-hedged return of the 1-month straddle bought on a given trading day, say day 0, we use the information of day 1, day 2, up to day 22, assuming that there are 22 trading days before the straddle maturity date. Then, for the delta-hedged return of the 1-month straddle bought on day 1, we use information of day 2, day 3, up to day 23. Consequently, the delta-hedged returns of day 0 and day 1 straddles use information from an overlapping period between day 2 and day 22. There is a concern whether our earlier evidence of a negative risk premium is driven by the common information in the overlapping periods. To address this issue, we adopt the following two approaches:

In the first approach, we construct a time series of non-overlapping delta-hedged straddle return for each currency. Specifically, for each currency, we construct a monthly series of delta-hedged returns on the 1-month straddles bought at the first trading day of every month in our sample period.[12] As the delta-hedged returns of the beginning-of-month straddle only depend on the information of the trading days in the same month, they are non-overlapping. Panel A of Table 3 reports the summary statistics for the non-overlapping returns for the four major currencies. Consistent with the earlier results in Table 1, the mean delta-hedged returns are negative across all four currencies.

To ascertain whether the volatility risk premium remains negative for non-overlapping series, we run the following regression

$$y_t = \alpha + \gamma\sigma_t + y_{t-1} + \varepsilon_t \tag{15}$$

where y_t is the delta-hedged straddle return, and σ_t is the volatility quote. If the volatility risk is priced and has a negative premium, then we expect γ to be significant

[12] We consider only the 1-month maturity because too few non-overlapping delta-hedged returns are available for longer maturities for any meaningful analysis.

and negative. Panel B of Table 3 reports the results. The evidence supports the conclusion that volatility risk is priced and has a negative risk premium.

Insert Table 3 here

In the second approach, we remove the effect of the common information from the overlapping period by calculating the difference between two consecutive delta-hedged straddle returns. In other words, we study the difference series, $\Delta y_t = y_t - y_{t-1}$, where y_t is the delta-hedged return on a delta-neutral straddle bought on date t. Since the straddle prices differ between the two days and the straddle return is proportional to the volatility risk premium as equation (10) shows, we expect to observe the risk premium in the regression of the first difference of delta-hedged straddle return on the first difference of implied volatility. Therefore, we run the following regression for Δy_t:

$$\Delta \boldsymbol{y}_t = \alpha_{\boldsymbol{D}} + \gamma_{\boldsymbol{D}} \Delta \sigma_t + \beta_{\boldsymbol{D}1} \Delta \boldsymbol{y}_{t-1} + \beta_{\boldsymbol{D}2} \Delta \boldsymbol{y}_{t-2} + \beta_{\boldsymbol{D}3} \Delta \boldsymbol{y}_{t-3} + \varepsilon_t \tag{16}$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, σ_t is the volatility quoted for a delta-neutral straddle on date t, and $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}. We include three lags of the dependent variable to control for potential serial autocorrelation in Δy_t. If the volatility risk premium exists and is negative, we expect the coefficient of $\Delta\sigma_t$ to be significant and negative.

Table 4 reports the estimation results of equation (16). The coefficient of implied volatility, γ_D, is negative for all currencies at all maturities. The *t*-test statistic based on

Newey-West (1987) heteroskedasticity and autocorrelation consistent standard errors shows that γ is significantly different from zero in all cases. This evidence provides further support that market volatility risk is priced in currency option markets.

Insert Table 4 here

C. Term Structure of Volatility Risk Premium

The empirical results so far have shown that volatility risk is priced in the OTC currency option markets and it has a negative risk premium. However, they reveal further information about the term structure of the volatility risk premiums. Previous studies such as those of Campa and Chang (1995) and Xu and Taylor (1994) report that volatility itself is more volatile at short-term maturities than at long-term maturities. The pattern is also evident in Figure 1. This means that short-term options carry higher volatility risks than long-term ones. Hence, it is reasonable to expect that currency option buyers pay a higher volatility risk premium for shorter maturity options as a compensation to option sellers for bearing higher volatility risks. Consistent with this expectation, Table 1 shows that the average delta-hedged straddle return decreases when the option maturity is extended. Table 2 and table 4 show that the coefficients of implied volatility, γ and γ_D, also exhibit a term structure. Because γ is the coefficient of volatility, it can be regarded as the average delta-hedged straddle return per unit of volatility. We call this the unit delta-hedged straddle return. We observe that the magnitude of the unit delta-hedged straddle return decreases with maturity. Because the vega of at-the-money options is an increasing function of maturity (see, e.g., Hull (2003)), the downward sloping term structure in the magnitude of the unit delta-hedged straddle return is unlikely to be due to vega. This evidence, combined with equation (10), suggests that the magnitude of the volatility risk premium decreases with option maturity, which is consistent with the fact that short-term volatility is more volatile than long-term volatility.

To test whether the observed difference between the short-term volatility risk premium and the long-term volatility risk premium is statistically significant, we estimate the following model on the combined time series across the four maturities:

$$\begin{aligned} \Delta y_t = {} & \alpha_1 I_1 + \alpha_3 I_3 + \alpha_6 I_6 + \alpha_{12} I_{12} + \\ & \gamma_1 \Delta\sigma_{1,t} * I_1 + \gamma_3 \Delta\sigma_{3,t} * I_3 + \gamma_6 \Delta\sigma_{6,t} * I_6 + \gamma_{12} \Delta\sigma_{12,t} * I_{12} + \\ & \beta_1 \Delta y_{t-1} + \beta_2 \Delta y_{t-2} + \beta_3 \Delta y_{t-3} + \varepsilon_t \end{aligned} \tag{17}$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, $\sigma_{i,t}$ is the quoted volatility for the i-month maturity on date t, $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}, and I_i is the indicator variable of an observation for the i-month maturity with i being 1, 3, 6 or 12. We use α_i to allow different intercepts at different maturities.

The estimation results are reported in Table 5. The volatility risk premium presents a term structure for all four currencies. We use the Wald statistic to test two null hypotheses: one is $\gamma_1 = \gamma_{12}$ and the other $\gamma_1 + \gamma_3 = \gamma_6 + \gamma_{12}$. The test rejects the two null hypotheses in all cases, which suggests that the difference between short-term and long-term volatility risk premiums is significant. This finding implies that the option buyer is paying a significantly higher volatility risk premium to the option seller for the shorter maturity option.

Insert Table 5 here

VI. Robustness Analysis

A. Other Currency Pairs

To investigate whether our results are a special feature of the four currencies selected or whether they apply more broadly, we examine seven other currency pairs. They are selected based on the liquidity of the option contract and the availability of data. Four of the seven currency pairs are the Australian Dollar, Canadian Dollar, Norwegian Kroner, and New Zealand Dollar against the U.S. Dollar. The other three are cross currency pairs and they are the Japanese Yen against British Pound, the Japanese Yen against Euro, and the Euro against Swiss Franc.

As these seven currency pairs are less liquid than the four selected currency pairs in the OTC option market, Bloomberg does not have complete daily straddle quotes from June 1996 to December 2003. We include only observations before December 2003 that have complete data necessary for our empirical analysis. The sample size for each currency pairs is reported in Table 6.

We replicate the analysis based on Equations (16) and (17) for these seven currency pairs. Table 6 shows that the coefficient of implied volatility in equation (16) is negative and significant. This is consistent with the earlier observations for the four major currency pairs, and demonstrates that volatility risk is also priced in the OTC market for these seven currency pairs.

Insert Table 6 here

Table 7 reports the estimation results of Equation (17) and provides evidence on the term structure in volatility risk premium. Consistent with the evidence in the British Pound, Euro, Japanese Yen and Swiss Franc against U.S. dollar, the volatility risk premium presents a term structure for all seven currencies. The magnitude of the short-term risk premium is greater than its long-term counterpart. The two Wald tests show that the difference is significant.

Insert Table 7 here

B. Post-Asian Currency Crisis Period

In this subsection, we report a sub-period analysis that serves two purposes: to examine the temporal stability of the volatility risk premium, and to rule out the possibility that our main findings may be affected by the Asian currency crisis. We replicate the analysis for the post-crisis period between July 1, 1999 and December 31, 2002. Table 8 reports the results for the post-crisis period. We observe the same properties of the delta-hedged straddle returns as in Table 1. The main difference between Table 8 and Table 1 lies in the results for the Japanese Yen. During the post-crisis period, the mean return is significantly negative for the Yen, whereas it is not for the whole period. A possible explanation is that the Asian currency crisis affected the Yen more than the other three currencies, which causes the distribution of the Yen's implied volatility to differ a lot during and after the crisis. Figure 3 shows that the distribution is less right-skewed for the Yen in the post-crisis period than for the whole period.

Insert Table 8 here

Insert Figure 3 here

Table 9 reports the estimation results of Equation (16) for the post-Asian currency crisis period. It shows the same evidence as in Table 4 that the volatility risk premium is significantly negative for the four currencies and the four maturities under our study.

Insert Table 9 here

C. Impact of Jump Risk

Recent studies suggest that option prices account for not only the stochastic volatility in the return distribution of underlying assets, but also the potentially large tail events.[13] Theoretical option pricing models have been developed to incorporate both stochastic volatility and potential jumps in the underlying return process (see Pan (2002)

[13] See, for example, Bakshi, Cao, and Chen (1997), Bates (2000), Duffie, Pan, and Singleton (2000), Eraker, Johannes, and Polson (2000), and Pan (2002) for theoretical analysis and empirical evidence.

and the references therein). Hence, it is possible that part of the risk premium observed in our empirical results is due to jump risk rather than volatility risk. In this section, we conduct further analysis to show that the volatility risk premium is distinct from the jump risk premium and is indeed a portion of the option price.

To isolate the potential effect of jump risk, we need to examine the delta-hedged straddle returns for a sample where jump fears are much less pronounced. We do so by identifying the days where jump fears are high and exclude them from the sample. We argue that large moves in currency prices cause market participants to revise upwards their expectation of future large moves. This is consistent with the fact that GARCH type models are adequate for the return process of financial assets (see, e.g., Bollerslev, Chou, and Kroner (1992)). Jackwerth and Rubinstein (1996) report that after the October 1987 market crash, the risk-neutral probability of a large decline in the equity market index is much higher than before the crash. Hence, jump fears are likely to be high after large moves in currency prices. We identify the dates when currency prices experienced large moves so that the daily percentage change is two standard deviations away from the mean daily percentage change in our sample period. The first column of Table 10 reports the number of days that experienced a large move in currency prices. We do not differentiate between negative and positive jumps because the straddle price is equally sensitive to moves in both directions. Take the British Pound as an example. Between June 3, 1996 and December 31, 2002, 103 days (about 6%) experienced large moves in the U.S. dollar price of the British Pound in either a positive or a negative direction. The Euro has a lesser number of large move days because of its shorter trading history. We found that the average delta-hedged straddle returns remain significantly negative for all currencies after we exclude from the sample the delta-hedged straddle returns of those days when large moves occurred and also the days immediately after.

Furthermore, we compare the mean and the median of delta-hedged straddle returns in the day before large moves with those in the day after. The results are reported in Table 10. The *t*- and Wilcoxon tests show that both the mean and median of the delta-hedged straddle returns are significantly negative in most cases before and after large moves.[14] However, the most salient feature is that, for all currencies and across all maturities, the delta-hedged straddle return is significantly more negative in the day after than the day before. To control for the effect of variability between the days on the before-versus-after comparison, we calculate the return difference between before and after for each large move day and compute the mean and median of the differences. The results are reported in the last two columns of Table 10. The within-day difference clearly shows that the magnitudes of delta-hedged straddle returns are significantly larger in the day after than the day before jumps. It is likely that after price jumps, the market perceives a high risk of jumps and thus option buyers pay an additional premium to option sellers for bearing jump risk on top of the volatility risk. This finding provides evidence that jump risk is priced in the currency option market. However, that the delta-hedged straddle returns are negative at most times, even on the days before jumps when

[14] A close look at the dates of large moves show that the dates are set widely apart, which makes it safe to assume independence in the sample of delta-hedged straddle returns and use t- and Wilcoxon tests. This also suggests that although large moves cause market participants to raise their expectations of future jumps, few large moves of the same magnitude happened consecutively because of the mean-reverting nature of the return process.

jump risk is much less pronounced, indicates that the volatility risk premium is distinct from and not subsumed by the jump risk premium.

Insert Table 10 here

D. Effect of Mis-measurement in the Delta Hedge Ratio

Extant theory (e.g. Hull and White (1987, 1988), Heston (1993) and others) suggests that using a delta hedge ratio computed on the basis of a constant volatility model such as the Garman-Kohlhagen model may cause bias in hedging performance when the volatility process is actually stochastic. The bias depends on the correlation between the volatility process and the underlying asset return process. To mitigate the potential bias in the delta hedge ratio, we use the modified Garman-Kohlhagen model in computing the hedge ratio, that is, the volatility is updated daily. Since this modified Garman-Kohlhagen model may not have fully corrected the mis-specification, we estimate the following model for the delta-hedged straddle returns:

(18) $$y_t = \alpha + \gamma\sigma_t + \Omega R_{t,t+\tau} + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 y_{t-3} + \varepsilon_t$$

where the additional variable, $R_{t,t+\tau}$, is the return in spot currency prices over the straddle maturity period from t to $t+\tau$. We use $R_{t,t+\tau}$ to capture the potential effect of a systematic hedging bias. We construct two time series of at-the-money straddles for each currency for the 1-month and the 3-month maturity period: one series is for positive $R_{t,t+\tau}$, and the other series is for negative $R_{t,t+\tau}$. The first series is designed to capture a sample for which the spot market is upward trending. The second series represents a sample for which there is a downward trending spot market[15].

If the modified Garman-Kohlhagen model systematically under-hedges (over-hedges), we expect Ω to be positive (negative) for an upward trending spot market and Ω to be negative (positive) for a downward trending spot market.[16]

Insert Table 11 here

The regression results are reported in Table 11. All the Ω coefficients are positive for upward trending markets and the majority is negative for downward trending markets. However, not all of the Ω coefficients are significantly different from zero, particularly for downward trending markets. This suggests that the modified Garman-Kohlhagen model used does not fully correct for the mis-specification in all cases. It tends to under-hedge, so that the delta-hedged straddle return is upward biased. However, the important thing is that in all regressions, after we explicitly account for the possible bias in the hedge ratio, the γ coefficient of implied volatility is significantly different from zero and is negative. The only exception is the γ coefficient of the Euro currency in the upward trending market. This provides further support for the negative volatility risk premium in the OTC currency option market.

---

[15] Time series for straddles with a 6-month and 12-month maturity period are not used in this robustness test because the use of the $R_{t,t+\tau}$ criteria cannot fully capture the spot market trend during the option life.

[16] Bakshi and Kapadia (2003) employ a similar robustness test in their study of the equity index option market.

We conduct another test to assess the reasonableness of the estimated deltas hedge ratio. In this test we compute two daily delta neutral straddle returns: (1) the first day price changes of a new delta neutral straddle price and the estimated second day price (R1), and (2) the first day price changes of successive new delta neutral straddle prices (R2). We compute the two price changes for 1-month, 3-month, 6-month, and 1-year straddles for GBP, CHF, JPY, and EUR.

The daily returns of a delta neutral straddle should on average give an expected return less than the risk free rate in the presence of a negative volatility risk premium. We also expect that R1 on average is less than R2. Since a long position in delta neutral straddle earns a large profit when there are jumps in the spot price, we exclude those days when there are jumps in spot price. We define a jump as the daily percentage change in spot price that is two standard deviations away from the mean daily percentage change in our sample period. This definition is consistent with the definition we used in section VI, subsection C. Our empirical results show that the means of R1 are negative and statistically significant for all cases, except 1-year GBP straddles. Moreover, the means of R2 are higher than the means of R1 for all cases. The results provide support on the reasonableness of our delta estimates.[17]

[17] We thank an anonymous referee for suggesting this robustness test. The empirical results are available upon request.

E. Potential Biases During Periods of Increasing or Decreasing Volatility

As a final robustness check, we investigate whether the trend in the volatility process affects our conclusions. We identify two trending periods for both the British Pound and the Japanese Yen: one with an increasing trend in observed volatility quotes and the other with a decreasing trend. For the British Pound, the decreasing trend occurred between June 6, 1998 and August 14, 1998, while the increasing trend occurred between June 25, 1999 and September 17, 1999. For the Japanese Yen, the decreasing and increasing trends extend from February 19, 1999 to June 25, 1999, and from November 10, 2000 to March 30, 2001, respectively. We replicate the empirical analysis based on regressions (14) and (16) for the 1-month and 3-month delta-hedged straddle returns in these four trending periods and obtain similar evidence that supports the existence of negative volatility risk premium.[18]

VII. Conclusion

Substantial evidence has been documented that volatility in both the equity market and the currency market is stochastic. This exposes investors to the risk of changing volatility. Although several studies show that volatility risk is priced in the equity index option market and that the volatility risk premium is negative, there are few studies about the issue in the currency option market. This paper contributes to the literature in this direction.

[18] The empirical results are not included, but available upon request.

Using a large database of daily ask volatility quotes on at-the-money delta neutral straddles in the OTC currency option market, we first find the volatility risk is priced in four major currencies – the British Pound, Euro, Japanese Yen, and Swiss Franc - across a wide range of maturity terms between 1 month and 12 months. Second, we provide direct evidence of the sign of the volatility risk premium. The risk premium is negative for all four major currencies, suggesting that buyers in the OTC currency option market pay a premium to sellers as compensation for bearing the volatility risk. Third, we find that the volatility risk premium has a term structure where the magnitude of the volatility risk premium decreases in maturity. This study is the first to provide empirical evidence of the term structure of the volatility risk premium. Although previous studies have documented that short-term volatility has higher variability than long-term volatility (e.g. Campa and Chang (1995) and Xu and Taylor (1994)), no study has investigated its implication on the volatility risk premium. Fourth, there is some evidence that jump risk is also priced in OTC market. However, the observed volatility risk premium is distinct from and not subsumed by the possible jump risk premium. These findings are robust to various sensitivity analyses on risk-free interest rate, option delta computation, and specification of empirical model.

REFERENCES

Bakshi, G., C. Cao, and Z. Chen. “Empirical Performance Of Alternative Option Pricing Models.” Journal of Finance, 52 (1997), 2003-2049.

Bakshi, G., and N. Kapadia. “Delta-Hedged Gains and the Negative Market Volatility Risk Premium.” Review of Financial Studies, 16 (2003), 527-566.

Bank for International Settlement. Central Bank Survey of Foreign Exchange and Derivatives Market Activity 1995. Basle, (1996).

Bank for International Settlement. BIS Quarterly Review – International Banking and Financial Market Developments. Basle, (1997).

Bank for International Settlement. Central Bank Survey of Foreign Exchange and Derivatives Market Activity 2001. Basle, (2002).

Bank for International Settlement. BIS Quarterly Review – International Banking and Financial Market Developments. Basle, (2003).

Bates, D. “Post-’87 Crash Fears in S&P 500 Futures Options.” Journal of Econometrics 94 (2000), 181-238.

Bollerslev, T., R.Y. Chou, and K.F. Kroner. “ARCH Modeling in Finance.” Journal of Econometrics, 52 (1992), 5-59.

Campa, J., and K.H. Chang. “Testing the Expectations Hypothesis on the Term Structure of Volatilities.” Journal of Finance 50 (1995), 529-547.

Campa, J., and K.H. Chang. "The Forecasting Ability Of Correlations Implied In Foreign Exchange Options," Journal of International Money and Finance, 17 (1998), 855-880.

Chesney, M., and L. Scott. “Pricing European Currency Options: A Comparison of the Modified Black-Scholes Model and a Random Variance Model,” Journal of Financial and Quantitative Analysis, 24(1989), 267-284.

Coval, J., and T. Shumway. “Expected Option Returns.” Journal of Finance, 56 (2001), 983-1009.

Covrig, V., and B.S., Low. “The Quality of Volatility Traded on the Over-the-Counter Currency Market: A Multiple Horizons Study.” Journal of Futures Markets, 23 (2003), 261-285.

Cox, J., J. Ingersoll, and S. Ross. “An Intertemporal General Equilibrium Model of Asset Prices.” Econometrica, 53 (1985), 363-384.

De Santis, G., and B. Gerard. "How Big Is The Premium For Currency Risk? " Journal of Financial Economics, 49 (1998), 375-412.

Duffie, D., J. Pan, and K. Singleton. “Transform Analysis and Asset Pricing for Affine Jump-diffusions.” Econometrica, 68 (2000), 1343-1376.

Dumas, B., and B. Solnik. "The World Price Of Foreign Exchange Risk." Journal of Finance, 50 (1995), 445-479.

Eraker, B., M.S. Johannes, and N.G., Polson. “The Impact of Jumps in Returns and Volatility.” Working paper, University of Chicago, (2000).

Garman, B., and S. Kohlhagen. “Foreign Currency Option Values.” Journal of International Money and Finance, 2 (1983), 231-237.

Heynen, R., A. Kemna, and T. Vorst. “Analysis of the Term Structure of Implied Volatilities.” Journal of Financial and Quantitative Analysis, 29 (1994), 31-56.

Heston, S. “A Closed Form Solution for Options with Stochastic Volatility with Applications to Bond and Currency Options.” Review of Financial Studies, 6 (1993), 327-343.

Hull, J., and A. White. "The Pricing Of Options On Assets With Stochastic Volatilities," Journal of Finance, 42 (1987), 281-300.

Hull, J. and A. White. "An Analysis Of The Bias In Option Pricing Caused By Stochastic Volatility," Advances in Futures and Options Research, 3 (1988), 29-61.

Hull, J. *Options, Futures, and Other Derivatives,* 5th edition, Prentice Hall (2003).

Jackwerth, J., and M. Rubinstein. “Recovering Probability Distributions From Option Prices.” Journal of Finance, 51 (1996), 1611-1631.

Jorion, P. “Predicting Volatility in the Foreign Exchange Market.” Journal of Finance, 50 (1995), 507-528.

Lamoureux, G., and W. Lastrapes. “Forecasting Stock-Return Variance: Toward An Understanding of Stochastic Implied Volatilities.” Review of Financial Studies, 6 (1993), 293-326.

Melino, A., and S. Turnbull. “Pricing Foreign Currency Options with Stochastic Volatility.” Journal of Econometrics, 45 (1990), 239-265.

Melino, A., and S. Turnbull. “Misspecification And The Pricing And Hedging Of Long-Term Foreign Currency Options.” Journal of International Money and Finance, 14 (1995), 373-393.

Neely, C. “Forecasting Foreign Exchange Volatility: Is Implied Volatility the Best We Can Do?” working paper, Federal Reserve Bank of St. Louis (2003).

Newey, W.K., and K.D. West. “A Simple Positive Semi-definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix.” Econometrica, 55 (1987), 702-708.

Pan, J. “The Jump-risk Premia Implicit in Options: Evidence from an Integrated Time Series Study.” Journal of Financial Economics, 63 (2002), 3-50.

Sarwar, G. “Is Volatility Risk for British Pound Priced in U.S. Options Markets?” The Financial Review, 36 (2001), 55-70.

Stein, J. “Overreactions in the Options Market.” Journal of Finance, 44 (1989), 1011-1024.

Taylor, S., and X. Xu. “The Incremental Volatility Information In One Million Foreign Exchange Quotations.” Journal of Empirical Finance, 4 (1997), 317-340.

Wilmott, P. *Derivatives*, John Wiley & Sons (1998).

Xu, X., and S. Taylor. “The Term Structure Of Volatility Implied By Foreign Exchange Options.” Journal of Financial and Quantitative Analysis, 29 (1994), 57-74.

Table 1: Summary statistics of the delta-hedged straddle returns for the whole sample period

The U.S. dollar delta-hedged straddle profit (loss) from holding the dynamically delta-hedged portfolio until maturity is computed by

$$\Pi_{t,t+\tau} = Max(x_{t+\tau} - k, k - x_{t+\tau}, 0) - f_t - \sum_{n=0}^{N-1} \Delta_{t_n} (x_{t_n} - x_{t_{n+1}}) - \sum_{n=0}^{N-1} (r_t f_t - (r_t - q_t)\Delta_{t_n} x_{t_n}) \frac{\tau}{N}$$

where f_t is the straddle premium at time t, $x_{t+\tau}$ is the currency price at the maturity $t+\tau$, k is the strike price of the straddle, Δ_{t_n} is the delta of the long straddle, r_t and q_t are the domestic and foreign interest rates. The delta-hedged straddle return is calculated as $\Pi_{t,t+\tau}$ divided by the straddle contract size in U.S. Dollar. We annualize the return to make it comparable across maturities. We report summary statistics on the return for four currencies at four standard maturities. For each combination of currency and maturity, the delta-hedged straddle return comprises a time series of one observation on each trading day. We fit an AR(3) process to the time series and test whether the intercept is zero. This is equivalent to a test of whether the mean delta-hedged straddle return is equal to zero. The sample period is from June 1996 to December 2002 for the British Pound, the Japanese Yen, and the Swiss Franc, and January 1999 to December 2002 for the Euro.

Maturity	Obs. #	% of negative return	Sample mean	Sample standard deviation	Autocorrelation coefficient Lag 1	Autocorrelation coefficient Lag 2	Autocorrelation coefficient Lag 3	Partial autocorrelation coefficient Lag 1	Partial autocorrelation coefficient Lag 2	Partial autocorrelation coefficient Lag 3	AR(3) Intercept Estimate	AR(3) Intercept P-value
Panel A: British Pound (GBP)												
1 month	1705	71%	-0.0239	0.0504	0.863	0.771	0.700	0.863	0.107	0.052	-0.0028	0.0001
3 months	1705	77%	-0.0179	0.0244	0.953	0.921	0.893	0.953	0.136	0.054	-0.0007	0.0046
6 months	1705	83%	-0.0152	0.0167	0.957	0.921	0.904	0.957	0.067	0.214	-0.0003	0.0162
12 months	1705	85%	-0.0130	0.0112	0.948	0.920	0.915	0.948	0.207	0.278	-0.0002	0.0219
Panel B: Euro (EUR)												
1 month	1027	58%	-0.0122	0.0626	0.830	0.724	0.638	0.830	0.110	0.037	-0.0018	0.1005
3 months	1027	67%	-0.0115	0.0259	0.952	0.916	0.888	0.952	0.110	0.074	-0.0005	0.0822
6 months	1027	64%	-0.0087	0.0191	0.977	0.960	0.942	0.977	0.099	-0.005	-0.0002	0.1542
12 months	1027	58%	-0.0072	0.0154	0.989	0.979	0.970	0.989	0.042	0.046	-0.0001	0.1966

Table 1 (Cont'd)

Maturity	Obs. #	% of negative return	Sample mean	Sample standard deviation	Autocorrelation coefficient			Partial autocorrelation coefficient			AR(3) Intercept	
					Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3	Estimate	P-value
Panel C: Japanese Yen (JPY)												
1 month	1705	59%	-0.0105	0.0974	0.877	0.768	0.699	0.877	-0.006	0.117	-0.0012	0.3507
3 months	1705	60%	-0.0085	0.0440	0.930	0.876	0.826	0.930	0.083	0.017	-0.0005	0.2502
6 months	1705	68%	-0.0055	0.0398	0.938	0.902	0.869	0.938	0.183	0.053	-0.0001	0.6671
12 months	1705	54%	-0.0033	0.0248	0.920	0.879	0.822	0.920	0.214	-0.069	-0.0002	0.3659
Panel D: Swiss Franc (CHF)												
1 month	1705	58%	-0.0047	0.0647	0.845	0.732	0.651	0.845	0.063	0.067	-0.0005	0.5344
3 months	1705	65%	-0.0085	0.0272	0.940	0.899	0.868	0.940	0.130	0.091	-0.0004	0.0747
6 months	1705	61%	-0.0059	0.0179	0.961	0.932	0.904	0.961	0.107	0.022	-0.0002	0.0696
12 months	1705	66%	-0.0052	0.0112	0.971	0.955	0.935	0.971	0.212	-0.019	-0.0001	0.0328

Table 2: Regression of the delta-hedged straddle return on implied volatility

This table presents the estimated results for the regression model

$$y_t = \alpha + \gamma\sigma_t + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 y_{t-3} + \varepsilon_t$$

where y_t is the delta-hedged straddle return, and σ_t is the implied volatility. We include three lagged variables, y_{t-1}, y_{t-2}, and y_{t-3}, to control for serial correlation in the time series of delta-hedged straddle returns. We estimate one model for each combination of currency and maturity. Our objective is to test the null hypothesis that $\gamma = 0$.

Independent variables	1 month	3 months	6 months	12 months
Panel A: British Pound (GBP)				
Intercept	0.018**	0.009**	0.011**	0.009**
Implied vol.	-0.251**	-0.118**	-0.136**	-0.123**
Straddle return – lag 1	0.746**	0.694**	0.577**	0.634**
Straddle return – lag 2	0.064	0.249*	0.048	0.086
Straddle return – lag 3	0.059	-0.006	0.287	0.167
Adj. r-squared	0.753	0.897	0.856	0.848
Obs. #	1702	1702	1702	1702
Durbin-Watson statistic	1.978	1.958	1.928	1.898
Panel B: Euro (EUR)				
Intercept	0.018**	0.004**	0.002	0.001
Implied vol.	-0.178**	-0.044**	-0.015	-0.009
Straddle return – lag 1	0.859**	0.869**	0.917**	0.982**
Straddle return – lag 2	0.012	-0.086	0.036	0.008
Straddle return – lag 3	-0.019	0.173	0.037	0.003
Adj. r-squared	0.741	0.892	0.963	0.978
Obs. #	1024	1024	1024	1024
Durbin-Watson statistic	1.982	1.878	1.991	1.995

** significant at the 1% level
* significant at the 5% level

Table 2 (Cont'd)

Independent variables	1 month	3 months	6 months	12 months
Panel C: Japanese Yen (JPY)				
Intercept	0.171**	0.108**	0.050**	0.024*
Implied vol.	-1.474**	-0.942**	-0.419**	-0.202*
Straddle return - lag 1	0.316**	0.227**	0.371**	0.498**
Straddle return - lag 2	0.136**	0.142**	0.245**	0.252**
Straddle return - lag 3	0.156**	0.091*	0.201**	0.061
Adj. r-squared	0.621	0.686	0.741	0.798
Obs. #	1702	1702	1702	1702
Durbin-Watson statistic	1.171	0.858	1.428	1.581
Panel D: Swiss Franc (CHF)				
Intercept	0.029**	0.015**	0.012**	0.006**
Implied vol.	-0.268**	-0.146**	-0.110**	-0.054**
Straddle return - lag 1	0.789**	0.809**	0.886**	0.624**
Straddle return - lag 2	0.041	-0.025	-0.051	0.325**
Straddle return - lag 3	0.051	0.136**	0.079	-0.005
Adj. r-squared	0.777	0.879	0.908	0.911
Obs. #	1702	1702	1702	1702
Durbin-Watson statistic	1.974	1.973	1.928	1.815

** significant at the 1% level
*   significant at the 5% level

Table 3: Non-overlapping straddle returns

For each currency, we construct a non-overlapping monthly series of delta-hedged straddle returns on the 1-month straddles bought at the first trading day of every month in the sample period. Panel A shows the summary statistics for non-overlapping series. Panel B shows the results of estimating this regression:

$$y_t = \alpha + \gamma\sigma_t + y_{t-1} + \varepsilon_t$$

where y_t is the delta-hedged straddle return, and σ_t is the implied volatility quote. If the volatility risk is priced and has a negative premium, we expect γ to be significant and negative. The sample period is from June 1996 to December 2002 for the British Pound, the Japanese Yen, and the Swiss Franc, and January 1999 to December 2002 for the Euro.

	British Pound	**Euro**	**Japan. Yen**	**Swiss Franc**
Panel A. Summary statistics				
Obs. #	77	48	77	77
Mean	-0.0182	-0.0101	-0.0202	-0.0030
Std. Dev.	0.0541	0.0544	0.0835	0.0731
% of negative	66%	58%	63%	60%
Autocorrelation coefficient				
Lag 1	-0.1448	-0.1232	0.0746	-0.0976
Lag 2	-0.1504	-0.1380	0.2390	-0.0321
Lag 3	0.0300	0.0948	-0.0518	0.0517
Panel B. regression against implied vol				
Intercept	0.0359**	0.0531	0.0360	0.0496*
Implied vol.	-0.4225**	-0.4988*	-0.4073*	-0.5141*
Lag 1	0.8969**	0.6944**	0.7660**	0.8611**
Adj. r-squared	0.8514	0.5331	0.7548	0.8584
Durbin-Watson	1.8082	2.1030	1.4851	1.7141

** significant at the 1% level
* significant at the 5% level

Table 4: Regression of the first difference of delta-hedged straddle return on the first difference of implied volatility

This table presents the estimated results for the regression model

$$\Delta y_t = \alpha_D + \gamma_D \Delta\sigma_t + \beta_{D1}\Delta y_{t-1} + \beta_{D2}\Delta y_{t-2} + \beta_{D3}\Delta y_{t-3} + \varepsilon_t$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, σ_t is the volatility quoted for a delta-neutral straddle on date t, and $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}. We include three lagged dependent variables to control for serial autocorrelation. One regression model is estimated for each combination of currency and maturity. The objective is to test the null hypothesis that $\gamma_D = 0$.

Independent variables	1 month	3 months	6 months	12 months
Panel A: British Pound (GBP)				
Intercept	0.0001	0.0001	0.0001	0.0001
Δ Implied vol.	-2.9214**	-1.5621**	-1.0189**	-0.7190**
Δ Straddle return – lag 1	-0.1852**	-0.2628**	-0.3466**	-0.2696**
Δ Straddle return – lag 2	-0.1163**	0.0135	-0.2859**	-0.1839
Δ Straddle return – lag 3	-0.0796**	0.0336	0.0713	0.0096
Obs. #	1701	1701	1701	1701
Adj. r-squared	0.2110	0.2506	0.2337	0.2084
Durbin-Watson statistic	2.1016	2.1082	2.0589	1.9941
Panel B: Euro (EUR)				
Intercept	0.0000	-0.0001	-0.0001	-0.0001
Δ Implied vol.	-2.6459**	-1.6170**	-1.1664**	-0.8543**
Δ Straddle return – lag 1	-0.0633	-0.1109**	-0.0835**	-0.0370
Δ Straddle return – lag 2	-0.0360	-0.1930*	-0.0326	0.0001
Δ Straddle return – lag 3	-0.1699*	-0.0833	-0.0082	-0.0457
Obs. #	1023	1023	1023	1023
Adj. r-squared	0.1427	0.2768	0.3114	0.3137
Durbin-Watson statistic	2.0810	1.8912	2.1098	2.0541

** significant at the 1% level
*   significant at the 5% level

Table 4 (Cont'd)

Independent variables	1 month	3 months	6 months	12 months
Panel C: Japanese Yen (JPY)				
Intercept	0.0000	0.0001	0.0001	0.0000
Δ Implied vol.	-2.4670**	-1.4187**	-0.8722**	-0.4115**
Δ Straddle return - lag 1	-0.0546*	-0.0225**	-0.0923	-0.1223*
Δ Straddle return - lag 2	-0.0527	-0.0099	-0.0799	-0.0315
Δ Straddle return - lag 3	-0.0355	-0.0206	-0.0635	-0.0752
Obs. #	1701	1701	1701	1701
Adj. r-squared	0.8831	0.9545	0.8244	0.5919
Durbin-Watson statistic	2.1641	2.3060	2.2903	2.2432
Panel D: Swiss Franc (CHF)				
Intercept	0.0001	0.0000	0.0000	0.0001
Δ Implied vol.	-2.8374**	-1.6060**	-1.1459**	-0.7615**
Δ Straddle return - lag 1	-0.1513**	-0.1249**	-0.0039	-0.2461**
Δ Straddle return - lag 2	-0.0952**	-0.1592**	-0.1209	-0.0077
Δ Straddle return - lag 3	-0.0208	-0.0883*	-0.0476	0.0851
Obs. #	1701	1701	1701	1701
Adj. r-squared	0.1477	0.2950	0.3030	0.3392
Durbin-Watson statistic	2.0398	2.1151	1.9904	2.0218

** significant at the 1% level
*   significant at the 5% level

Table 5: Pooled regression of the first difference of delta-hedged straddle return on the first difference of implied volatility

We pool the delta-hedged straddle returns for four maturities and estimate the following model for each currency

$$\Delta y_t = \alpha_1 I_1 + \alpha_3 I_3 + \alpha_6 I_6 + \alpha_{12} I_{12} + \gamma_1 \Delta\sigma_{1,t} * I_1 + \gamma_3 \Delta\sigma_{3,t} * I_3 + \gamma_6 \Delta\sigma_{6,t} * I_6 + \gamma_{12} \Delta\sigma_{12,t} * I_{12} + \beta_1 \Delta y_{t-1} + \beta_2 \Delta y_{t-2} + \beta_3 \Delta y_{t-3} + \varepsilon_t$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, $\sigma_{i,t}$ is the quoted volatility for the i-month maturity on date t, $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}, and I_i is the indicator variable of an observation for the i-month maturity with i being 1, 3, 6 or 12. We use α_i to allow different intercepts at different maturities. Our main focus is on γ_i s, which measures the unit delta-hedged straddle return at different maturities. The sample period is from June 1996 to December 2002 for the British Pound, the Japanese Yen, and the Swiss Franc, and January 1999 to December 2002 for the Euro.

	Currency			
Independent variables	**GBP**	**EUR**	**JPY**	**CHF**
Dummy - 1 month	0.0001	0.0000	0.0000	0.0001
Dummy - 3 months	0.0001	-0.0001	0.0001	0.0000
Dummy - 6 months	0.0001	-0.0001	0.0001	0.0000
Dummy - 12 months	0.0000	-0.0001	0.0000	0.0001
Δ Implied vol. - 1 month	-2.9198**	-2.6396**	-2.4747**	-2.8370**
Δ Implied vol. - 3 months	-1.5518**	-1.6121**	-1.4014**	-1.6082**
Δ Implied vol. – 6 months	-1.0541**	-1.1724**	-0.8916**	-1.1115**
Δ Implied vol. – 12 months	-0.7349**	-0.8544**	-0.4270**	-0.7804**
Δ Straddle return - lag 1	-0.2078**	-0.0654	-0.0495**	-0.1469**
Δ Straddle return - lag 2	-0.1198**	-0.0423	-0.0439	-0.0994**
Δ Straddle return - lag 3	-0.0526	-0.1645*	-0.0334	-0.0253
Obs. #	6804	4092	6804	6804
Adj. r-squared	0.2079	0.1509	0.8933	0.1624
Durbin-Watson statistic	2.0964	2.0786	2.2042	2.0451
Wald test for H_0: $\gamma_1 = \gamma_{12}$				
Statistic	173.8484	81.5774	1703.0080	120.5293
(p-value)	(0.00)	(0.00)	(0.00)	(0.00)
Wald test for H_0: $\gamma_1 + \gamma_3 = \gamma_6 + \gamma_{12}$				
Statistic	188.4576	96.8067	1863.0928	158.5117
(p-value)	(0.00)	(0.00)	(0.00)	(0.00)

** significant at the 1% level
* significant at the 5% level

Table 6: Regression of the first difference of delta-hedged straddle return on the first difference of implied volatility for seven other currency pairs

This table presents the estimated results of the following regression model for seven other currency pairs

$$\Delta y_t = \alpha_D + \gamma_D \Delta\sigma_t + \beta_{D1}\Delta y_{t-1} + \beta_{D2}\Delta y_{t-2} + \beta_{D3}\Delta y_{t-3} + \varepsilon_t$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, σ_t is the volatility quoted for a delta-neutral straddle on date t, and $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}. We include three lagged dependent variables to control for serial autocorrelation. One regression model is estimated for each combination of currency and maturity. The objective is to test the null hypothesis, $\gamma_D = 0$. Some currency pairs in this table have smaller number of observations. This is due to the fact that Bloomberg does not have complete daily straddle quotes from June 1996 to December 2003. We include only observations before December 2003 that have complete data necessary for the empirical analysis.

Independent variables	1 month	3 months	6 months	12 months
Panel A: EUR/CHF				
Intercept	0.0000	0.0001	0.0000	0.0000
Δ Implied vol.	-2.6953**	-1.6269**	-1.1451**	-0.8314**
Δ Straddle return - lag 1	-0.0958	-0.1025*	-0.0747	0.0198
Δ Straddle return - lag 2	-0.0207	-0.0930*	-0.0894	-0.0504
Δ Straddle return - lag 3	0.0050	-0.1020*	0.0172	-0.0754
Obs. #	809	823	881	1038
Adj. r-squared	0.1500	0.4065	0.3519	0.5520
Durbin-Watson statistic	2.0743	2.1536	2.0881	1.9810
Panel B: YEN/GBP				
Intercept	0.0008	0.0002	0.0000	0.0000
Δ Implied vol.	-2.5397**	-1.6906**	-1.1327**	-0.6751**
Δ Straddle return - lag 1	-0.0724	-0.0665	-0.1262*	0.0015
Δ Straddle return - lag 2	-0.2064*	-0.1295**	-0.0189	-0.0178
Δ Straddle return - lag 3	-0.1116**	-0.1262**	-0.1821	-0.0639*
Obs. #	1312	1312	1312	1312
Adj. r-squared	0.1960	0.3508	0.2825	0.6062
Durbin-Watson statistic	2.0067	1.9588	2.1252	2.0230
Panel C: YEN/EUR				
Intercept	-0.0003	0.0000	0.0000	0.0000
Δ Implied vol.	-2.6111**	-1.5578**	-1.0682**	-0.7099**
Δ Straddle return - lag 1	-0.0664	-0.1145*	-0.0619	-0.0488*
Δ Straddle return - lag 2	-0.0939*	-0.1176*	-0.0365	0.0023
Δ Straddle return - lag 3	-0.0045	-0.0559	-0.0175	0.0413
Obs. #	1038	1038	1038	1038
Adj. r-squared	0.1721	0.2685	0.7806	0.5378
Durbin-Watson statistic	2.0881	2.1016	2.2408	2.1498

** significant at the 1% level
*   significant at the 5% level

Table 6 (Cont'd)

Independent variables	1 month	3 months	6 months	12 months
Panel D: Australian (AUD)				
Intercept	0.0000	0.0000	0.0000	0.0000
Δ Implied vol.	-2.5600**	-1.5400**	-1.0200**	-0.9300**
Δ Straddle return - lag 1	-0.0974**	-0.1463**	-0.1287**	-0.0257*
Δ Straddle return - lag 2	-0.0773*	-0.0149	-0.0535	-0.0115
Δ Straddle return - lag 3	-0.0269	-0.0663*	-0.0120	-0.0188
Obs. #	1679	1678	1680	1713
Adj. r-squared	0.0853	0.1358	0.1669	0.9415
Durbin-Watson statistic	2.0574	2.0652	2.0914	2.2327
Panel E: Canadian Dollar (CAD)				
Intercept	-0.0009	-0.0003	-0.0001	-0.0002
Δ Implied vol.	-2.9158**	-2.2620**	-0.8643**	-0.7757**
Δ Straddle return – lag 1	-0.2000**	0.0638	-0.2799**	-0.1132
Δ Straddle return – lag 2	-0.1590**	-0.0618	-0.1879**	-0.2699
Δ Straddle return – lag 3	0.0005	0.0305	-0.0752	-0.1786
Obs. #	298	168	137	60
Adj. r-squared	0.2663	0.5639	0.5337	0.3782
Durbin-Watson statistic	2.1184	2.2678	2.0147	2.0831
Panel F: Norwegian Kroner (NOK)				
Intercept	-0.0009	0.0002	0.0000	0.0000
Δ Implied vol.	-2.6090**	-1.3140**	-0.9449**	-0.7532**
Δ Straddle return – lag 1	-0.2202**	-0.2013**	-0.1969**	-0.1989**
Δ Straddle return – lag 2	-0.1640**	-0.1552	-0.0545	-0.0650
Δ Straddle return – lag 3	-0.0903*	-0.1037	0.0367	-0.0034
Obs. #	463	409	410	855
Adj. r-squared	0.1727	0.3092	0.4749	0.7013
Durbin-Watson statistic	2.0961	2.1529	1.9701	2.3951
Panel G: New Zealand Dollar (NZD)				
Intercept	-0.0013	-0.0001	-0.0001	-0.0001
Δ Implied vol.	-2.6634**	-1.4516**	-0.8526**	-0.6591**
Δ Straddle return - lag 1	-0.1802**	-0.1473*	-0.1472*	-0.0613
Δ Straddle return - lag 2	-0.0549	-0.0690	-0.0786	0.0329
Δ Straddle return - lag 3	-0.0318	-0.1491**	-0.1151*	-0.0855
Obs. #	667	576	504	480
Adj. r-squared	0.2093	0.2595	0.3701	0.4521
Durbin-Watson statistic	2.0985	2.0498	2.2401	1.9519

** significant at the 1% level
*   significant at the 5% level

Table 7: Pooled regression of the first difference of delta-hedged straddle return on the first difference of implied volatility for seven other currency pairs

We pool the delta-hedged straddle returns for four maturities and estimate the following model for seven other currency pairs

$$\Delta y_t = \alpha_1 I_1 + \alpha_3 I_3 + \alpha_6 I_6 + \alpha_{12} I_{12} + \gamma_1 \Delta\sigma_{1,t} * I_1 + \gamma_3 \Delta\sigma_{3,t} * I_3 + \gamma_6 \Delta\sigma_{6,t} * I_6 + \gamma_{12} \Delta\sigma_{12,t} * I_{12} + \beta_1 \Delta y_{t-1} + \beta_2 \Delta y_{t-2} + \beta_3 \Delta y_{t-3} + \varepsilon_t$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, $\sigma_{i,t}$ is the quoted volatility for the i-month maturity on date t, $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}, and I_i is the indicator variable of an observation for the i-month maturity with i being 1, 3, 6 or 12. We use α_i to allow different intercepts at different maturities. Our main focus is on γ_i s, which measures the unit delta-hedged straddle return at different maturities.

	Currency		
Independent variables	**EUR/CHF**	**YEN/GBP**	**YEN/EUR**
Dummy - 1 month	0.0000	0.0008	-0.0003
Dummy - 3 months	0.0001	0.0002	0.0000
Dummy - 6 months	0.0000	0.0001	0.0000
Dummy - 12 months	0.0000	0.0000	0.0000
Δ Implied vol. - 1 month	-2.6865**	-2.5426**	-2.6094**
Δ Implied vol. - 3 months	-1.6384**	-1.6866**	-1.5646**
Δ Implied vol. – 6 months	-1.1471**	-1.1307**	-1.0664**
Δ Implied vol. – 12 months	-0.8205**	-0.6564**	-0.7170**
Δ Straddle return - lag 1	-0.0956*	-0.0746	-0.0708*
Δ Straddle return - lag 2	-0.0329	-0.1956*	-0.0930*
Δ Straddle return - lag 3	-0.0101	-0.1153	-0.0097
Obs. #	3551	5248	4152
Adj. r-squared	0.1899	0.2091	0.2073
Durbin-Watson statistic	2.0848	2.0061	2.0905
Wald test for H_0: $\gamma_1 = \gamma_{12}$			
Statistic	14.4969	51.9282	37.6506
(p-value)	(0.00)	(0.00)	(0.00)
Wald test for H_0: $\gamma_1 + \gamma_3 = \gamma_6 + \gamma_{12}$			
Statistic	20.0182	65.2485	52.8223
(p-value)	(0.00)	(0.00)	(0.00)

** significant at the 1% level
*   significant at the 5% level

Table 7 (Cont'd)

	Currency			
Independent variables	**AUD**	**CAD**	**NOK**	**NZD**
Dummy - 1 month	0.0000	-0.0009	-0.0009	-0.0013
Dummy - 3 months	0.0000	-0.0003	0.0002	-0.0001
Dummy - 6 months	0.0000	-0.0001	0.0000	-0.0001
Dummy - 12 months	0.0000	-0.0001	0.0000	-0.0001
Δ Implied vol. - 1 month	-2.5600**	-2.9134**	-2.6085**	-2.6600**
Δ Implied vol. - 3 months	-1.5400**	-2.1086**	-1.3094**	-1.4761**
Δ Implied vol. – 6 months	-1.0300**	-0.8959**	-0.9484**	-0.8506**
Δ Implied vol. – 12 months	-0.9000**	-0.7963**	-0.7393**	-0.6393**
Δ Straddle return - lag 1	-0.1004**	-0.1812**	-0.2191**	-0.1761**
Δ Straddle return - lag 2	-0.0701*	-0.1504*	-0.1605**	-0.0563
Δ Straddle return - lag 3	-0.0307	-0.0016	-0.0875*	-0.0428
Obs. #	6750	663	2137	2227
Adj. r-squared	0.1245	0.2904	0.1985	0.2180
Durbin-Watson statistic	2.0621	2.1378	2.0997	2.1005
Statistic	35.6092	15.7488	45.3234	29.1777
(p-value)	(0.00)	(0.00)	(0.00)	(0.00)
Wald test for H_0: $\gamma_1 + \gamma_3 = \gamma_6 + \gamma_{12}$				
Statistic	42.3990	31.1340	46.8289	38.6366
(p-value)	(0.00)	(0.00)	(0.00)	(0.00)

** significant at the 1% level
* significant at the 5% level

Table 8: Summary statistics of the delta-hedged straddle return for the post-Asian currency crisis sub-period

The U.S. Dollar delta-hedged straddle profit (loss) from holding the dynamically delta-hedged portfolio until maturity is computed by

$$\Pi_{t,t+\tau} = Max\left(x_{t+\tau} - k, k - x_{t+\tau}, 0\right) - f_t - \sum_{n=0}^{N-1} \Delta_{t_n}\left(x_{t_n} - x_{t_{n+1}}\right) - \sum_{n=0}^{N-1}\left(r_t f_t - \left(r_t - q_t\right)\Delta_{t_n} x_{t_n}\right)\frac{\tau}{\mathrm{N}}$$

where f_t is the straddle premium at time t, $x_{t+\tau}$ is the currency price at the maturity $t+\tau$, k is the strike price of the straddle, Δ_{t_n} is the delta of the long straddle, r_t and q_t are the domestic and foreign interest rates. The delta-hedged straddle return is calculated as $\Pi_{t,\, t+\tau}$ divided by the straddle contract size in U.S. dollars. We annualize the return to make it comparable across maturities. We report summary statistics on the return for four currencies at four standard maturities. For each combination of currency and maturity, the delta-hedged straddle return comprises a time series of one observation on each trading day. We fit an AR(3) process to the time series and test whether the intercept is zero. This is equivalent to a test of whether the mean delta-hedged straddle return is equal to zero. The post-Asian currency crisis sub-period is from July 1999 to December 2002.

Maturity	Obs. #	% of negative return	Sample mean	Sample standard deviation	Autocorrelation coefficient			Partial autocorrelation coefficient			AR(3) Intercept	
					Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3	Estimate	P-value
Panel A: British Pound (GBP)												
1 month	902	70%	-0.0213	0.0484	0.846	0.750	0.692	0.846	0.123	0.113	-0.0027	0.0065
3 months	902	78%	-0.0185	0.0223	0.943	0.909	0.883	0.943	0.172	0.105	-0.0009	0.0204
6 months	902	82%	-0.0162	0.0165	0.939	0.893	0.881	0.939	0.087	0.289	-0.0003	0.0779
12 months	902	82%	-0.0133	0.0120	0.926	0.885	0.883	0.926	0.193	0.314	-0.0003	0.0666
Panel B: Euro (EUR)												
1 month	902	59%	-0.0130	0.0642	0.842	0.731	0.647	0.842	0.077	0.048	-0.0018	0.1117
3 months	902	68%	-0.0131	0.0264	0.959	0.927	0.900	0.959	0.091	0.047	-0.0005	0.0674
6 months	902	67%	-0.0106	0.0194	0.976	0.957	0.937	0.976	0.096	-0.012	-0.0003	0.0887
12 months	902	64%	-0.0093	0.0152	0.986	0.973	0.961	0.986	0.038	0.032	-0.0002	0.0317

Table 8 (Cont'd)

Maturity	Obs. #	% of negative return	Sample mean	Sample standard deviation	Autocorrelation coefficient			Partial autocorrelation coefficient			AR(3) Intercept	
					Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3	Estimate	P-value
Panel C: Japanese Yen (JPY)												
1 month	902	59%	-0.0138	0.0732	0.878	0.781	0.705	0.878	0.044	0.049	-0.0017	0.1653
3 months	902	66%	-0.0147	0.0363	0.886	0.816	0.745	0.886	0.144	-0.007	-0.0014	0.0385
6 months	902	82%	-0.0155	0.0278	0.803	0.711	0.628	0.803	0.186	0.038	-0.0020	0.0814
12 months	902	70%	-0.0096	0.0211	0.820	0.722	0.579	0.820	0.151	-0.145	-0.0017	0.0093
Panel D: Swiss Franc (CHF)												
1 month	902	55%	-0.0010	0.0660	0.834	0.720	0.656	0.834	0.081	0.119	-0.0002	0.8726
3 months	902	67%	-0.0095	0.0248	0.939	0.902	0.868	0.939	0.172	0.046	-0.0006	0.0376
6 months	902	68%	-0.0098	0.0165	0.950	0.915	0.884	0.950	0.125	0.038	-0.0004	0.0090
12 months	902	75%	-0.0085	0.0118	0.967	0.950	0.927	0.967	0.238	-0.037	-0.0003	0.0034

Table 9: Regression of the first difference of delta-hedged straddle return on the first difference of implied volatility for the post-Asian currency crisis sub-period

This table presents the estimated results for the regression model

$$\Delta \boldsymbol{y}_{t} = \alpha_{D} + \gamma_{D} \Delta \sigma_{t} + \beta_{D1} \Delta \boldsymbol{y}_{t-1} + \beta_{D2} \Delta \boldsymbol{y}_{t-2} + \beta_{D3} \Delta \boldsymbol{y}_{t-3} + \varepsilon_{t}$$

where y_t is the delta-hedged return on a delta-neutral straddle bought on date t, Δy_t is the difference between y_t and y_{t-1}, σ_t is the volatility quoted for a delta-neutral straddle on date t, and $\Delta\sigma_t$ is the difference between σ_t and σ_{t-1}. We include three lagged dependent variables to control for serial autocorrelation. One regression model is estimated for each combination of currency and maturity. The objective is to test the null hypothesis, $\gamma_D = 0$. The post-Asian currency crisis sub-period is from July 1999 to December 2002.

Independent variables	**1 month**	**3 months**	**6 months**	**12 months**
Panel A: British Pound (GBP)				
Intercept	0.0000	0.0001	0.0001	0.0001
Δ Implied vol.	-2.7502**	-1.5195**	-0.8710**	-0.6980**
Δ Straddle return – lag 1	-0.2161**	-0.3202**	-0.4009**	-0.2796**
Δ Straddle return – lag 2	-0.1601**	0.0299	-0.3309*	-0.1999
Δ Straddle return – lag 3	-0.0977*	0.0690	0.0624	0.0143
Obs. #	898	898	898	898
Adj. r-squared	0.2299	0.2488	0.2444	0.1878
Durbin-Watson statistic	2.0820	2.1123	2.0313	1.9780
Panel B: Euro (EUR)				
Intercept	0.0000	-0.0001	-0.0001	-0.0001
Δ Implied vol.	-2.5395**	-1.6108**	-1.1657**	-0.8574**
Δ Straddle return – lag 1	-0.0462	-0.0832	-0.0807*	-0.0389
Δ Straddle return – lag 2	-0.0393	-0.1986	-0.0329	-0.0010
Δ Straddle return – lag 3	-0.1793*	-0.0992	-0.0041	-0.0477
Obs. #	898	898	898	898
Adj. r-squared	0.0958	0.2812	0.3035	0.3020
Durbin-Watson statistic	2.0775	1.8289	2.1121	2.0527

** significant at the 1% level
*   significant at the 5% level

Table 9 (Cont'd)

Independent variables	1 month	3 months	6 months	12 months
Panel C: Japanese Yen (JPY)				
Intercept	-0.0002	0.0000	0.0001	0.0000
Δ Implied vol.	-3.1096**	-1.5436**	-1.1213**	-1.0263**
Δ Straddle return - lag 1	-0.1177**	-0.1973*	-0.3172**	-0.2011**
Δ Straddle return - lag 2	-0.0715*	-0.0437	-0.2103*	0.0399
Δ Straddle return - lag 3	-0.0987*	-0.1229	-0.2037*	-0.1415
Obs. #	898	898	898	898
Adj. r-squared	0.2816	0.1660	0.1522	0.1056
Durbin-Watson statistic	2.0697	2.0326	2.0549	2.0502
Panel D: Swiss Franc (CHF)				
Intercept	-0.0001	-0.0001	0.0000	0.0001
Δ Implied vol.	-2.5901**	-1.6449**	-1.1455**	-0.7238**
Δ Straddle return - lag 1	-0.1819**	-0.1715**	0.0063	-0.3168**
Δ Straddle return - lag 2	-0.1494**	-0.2061*	-0.1747	-0.0144
Δ Straddle return - lag 3	-0.0301	-0.1700*	-0.0274	0.1205
Obs. #	898	898	898	898
Adj. r-squared	0.1438	0.3324	0.2505	0.2891
Durbin-Watson statistic	2.0286	2.0904	1.9849	1.9902

** significant at the 1% level
*   significant at the 5% level

Table 10: Effect of jumps on the delta-hedged straddle return

We identify the day on which the daily percentage change in the currency price is two standard deviations away from the mean daily percentage change in our sample period. We examine the delta-hedged straddle returns in the day immediately before or after these price jumps. We do not differentiate between negative and positive jumps because the straddle price is equally sensitive to moves in both directions. The first column reports the number of days when price jumped. Take the British Pound as an example. Between June 3, 1996 and December 31, 2002, 103 days (about 6%) experienced large moves in the U.S. Dollar price of the British Pound in either a positive or a negative direction.

		Before jumps		**After jumps**		**Before vs. after**	
Maturity	**# of jumps**	**Mean (*p-value of t*-test)**	**Median (*p-value of* Wilcoxon test)**	**Mean (*p-value of t*-test)**	**Median (*p-value of* Wilcoxon test)**	**Mean (*p-value of t*-test)**	**Median (*p-value of* Wilcoxon test)**
Panel A: British Pound (GBP)							
1 month	103	-0.0009	0.0031	-0.0354	-0.0357	0.0345	0.0307
		(0.88)	(0.89)	(0.00)	(0.00)	(0.00)	(0.00)
3 months	103	-0.0167	-0.0199	-0.0257	-0.0275	0.0090	0.0078
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
6 months	103	-0.0155	-0.0150	-0.0188	-0.0194	0.0033	0.0025
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
12 months	103	-0.0149	-0.0177	-0.0166	-0.0188	0.0017	0.0010
		(0.00)	(0.00)	(0.00)	(0.00)	(0.10)	(0.00)
Panel B: Euro (EUR)							
1 month	53	0.0242	0.0265	-0.0251	-0.0116	0.0493	0.0442
		(0.03)	(0.01)	(0.01)	(0.05)	(0.00)	(0.00)
3 months	53	-0.0102	-0.0071	-0.0206	-0.0201	0.0104	0.0095
		(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
6 months	53	-0.0094	-0.0103	-0.0136	-0.0115	0.0042	0.0053
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
12 months	53	-0.0117	-0.0157	-0.0125	-0.0147	0.0008	0.0014
		(0.00)	(0.00)	(0.00)	(0.00)	(0.30)	(0.24)
Panel C: Japanese Yen (JPY)							
1 month	82	0.0257	0.0367	-0.0444	-0.0474	0.0701	0.0607
		(0.20)	(0.06)	(0.01)	(0.00)	(0.00)	(0.00)
3 months	82	0.0023	-0.0051	-0.0237	-0.0163	0.0259	0.0134
		(0.73)	(0.84)	(0.07)	(0.01)	(0.03)	(0.00)
6 months	82	-0.0010	-0.0059	-0.0078	-0.0155	0.0068	0.0071
		(0.87)	(0.26)	(0.17)	(0.02)	(0.00)	(0.00)
12 months	82	-0.0079	-0.0108	-0.0109	-0.0121	0.0030	0.0033
		(0.01)	(0.00)	(0.00)	(0.00)	(0.10)	(0.00)
Panel D: Swiss Franc (CHF)							
1 month	100	0.0353	0.0235	0.0004	-0.0017	0.0349	0.0309
		(0.00)	(0.00)	(0.95)	(0.66)	(0.00)	(0.00)
3 months	100	0.0005	0.0003	-0.0067	-0.0112	0.0072	0.0052
		(0.87)	(0.91)	(0.02)	(0.01)	(0.00)	(0.00)
6 months	100	-0.0058	-0.0101	-0.0087	-0.0130	0.0030	0.0023
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
12 months	100	-0.0066	-0.0058	-0.0076	-0.0072	0.0009	0.0006
		(0.00)	(0.00)	(0.00)	(0.00)	(0.08)	(0.07)

Table 11: Effect of mis-measurement in the delta hedge ratio

This table shows the estimation results for the regression model

$$y_t = \alpha + \gamma\sigma_t + \Omega R_{t,t+\tau} + \beta_1 y_{t-1} + \beta_2 y_{t-2} + \beta_3 y_{t-3} + \varepsilon_t$$

where y_t is the delta-hedged straddle return, σ_t is the implied volatility, and $R_{t\,t+\tau}$, is the return in spot currency prices over the maturity period from t to $t+\tau$. We use $R_{t\,t+\tau}$ to capture the potential systematic hedging bias. If the modified Garman-Kohlhagen model systematically under-hedges (over-hedges), we expect Ω to be positive (negative) for an upward trending spot market and Ω to be negative (positive) for a downward trending spot market. We include three lagged variables, y_{t-1}, y_{t-2}, and y_{t-3}, to control for serial correlation in the time series of delta-hedged straddle returns. We estimate one model for each currency for both 1-month and 3-month maturities. The sample period is from June 1996 to December 2002 for the British Pound, the Japanese Yen, and the Swiss Franc, and January 1999 to December 2002 for the Euro.

	Upward trending spot market				**Downward trending spot market**			
Independent variables	**British Pound**	**Euro**	**Japanese Yen**	**Swiss Franc**	**British Pound**	**Euro**	**Japanese Yen**	**Swiss Franc**
1-month maturity								
Intercept	0.009*	0.015*	0.120*	0.023**	0.019**	0.018	0.183**	0.028**
Implied vol.	-0.262**	-0.223**	-1.366**	-0.304**	-0.368**	-0.226*	-1.747**	-0.262**
Return in spot market	0.429**	0.314**	1.449**	0.337**	-0.541**	-0.287**	-0.394	-0.031
Straddle return - lag 1	0.678**	0.710**	0.310*	0.794**	0.713**	0.915**	0.209*	0.071**
Straddle return - lag 2	0.073	0.069	0.029	0.064	0.068	-0.026	0.114**	0.013
Straddle return - lag 3	0.061	0.053	0.232**	0.026	0.048	-0.043	0.066*	0.749
Obs. #	849	438	742	708	836	575	947	981
Adj. r-squared	0.761	0.687	0.642	0.806	0.773	0.770	0.712	0.712
Durbin-Watson stat.	1.889	1.930	1.393	1.989	1.968	1.935	0.894	1.895
3-month maturity								
Intercept	0.006**	-0.001	0.013	0.013**	0.015**	0.007*	0.126**	0.014**
Implied vol.	-0.081**	-0.027	-0.178*	-0.136**	-0.223**	-0.082**	-1.166**	-0.129**
Return in spot market	0.015	0.049**	0.151*	0.030*	-0.117**	-0.041*	0.024	0.001
Straddle return - lag 1	0.809**	0.818**	0.419*	0.799**	0.730**	0.790**	0.084*	0.099**
Straddle return - lag 2	0.070	-0.014	0.262**	0.052	0.099*	0.080	0.053*	0.053
Straddle return - lag 3	0.060	0.120*	0.054	0.072	0.073	0.087	0.051**	0.771*
Obs. #	751	373	642	672	895	600	1006	974
Adj. r-squared	0.937	0.901	0.772	0.905	0.901	0.917	0.824	0.888
Durbin-Watson stat.	1.919	1.701	0.963	1.937	1.833	1.766	0.455	1.833

** significant at the 1% level
***** significant at the 5% level

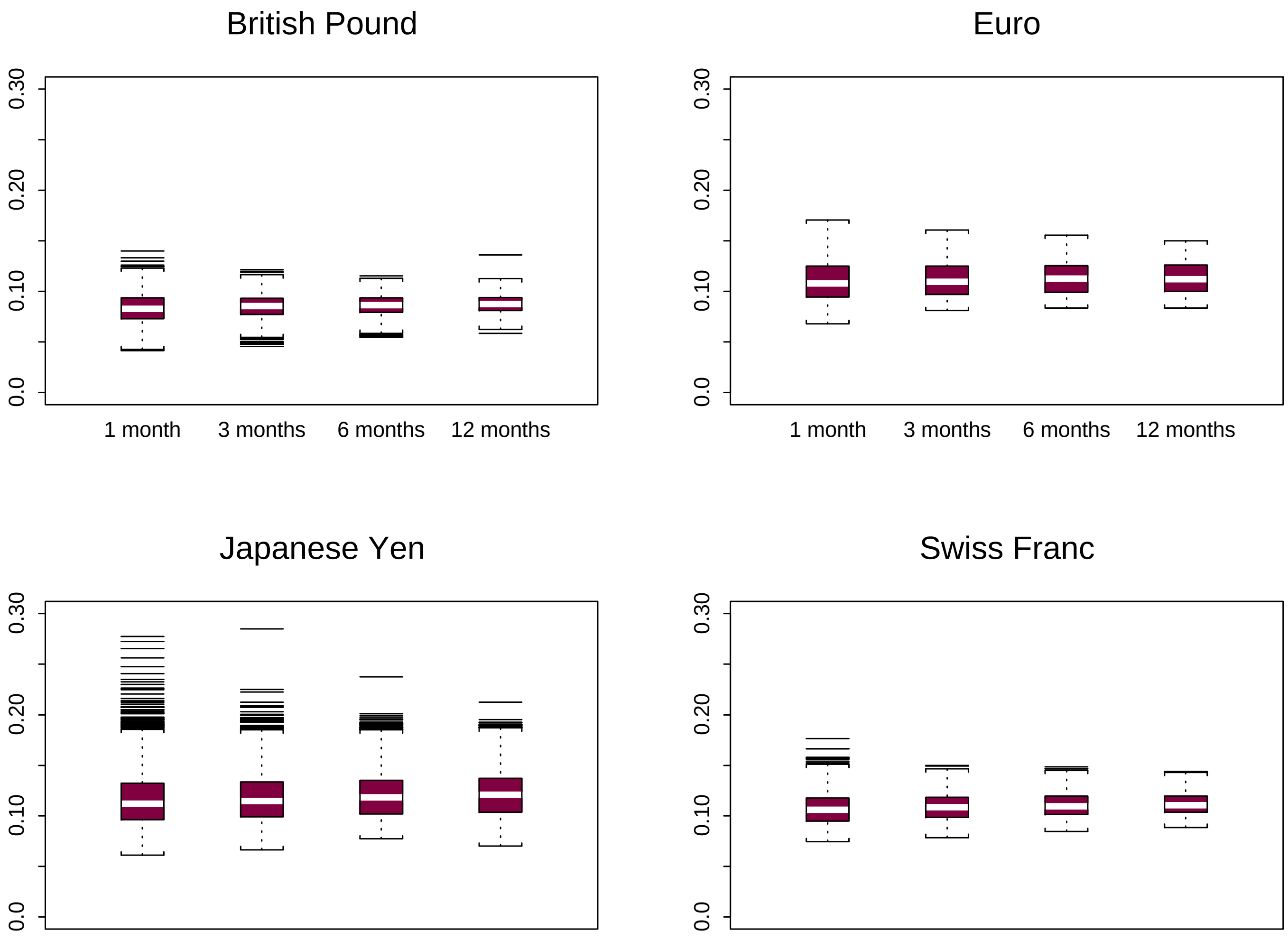

Figure 1: Distribution of implied volatility quotes for the whole sample period
This figure shows the boxplots of the daily implied volatility quotes for 1-month, 3-month, 6-month and 12-month at-the-money straddle between June 1996 and December 2002 for British Pound, Japanese Yen, and Swiss Franc, and between January 1999 and December 2002 for Euro.

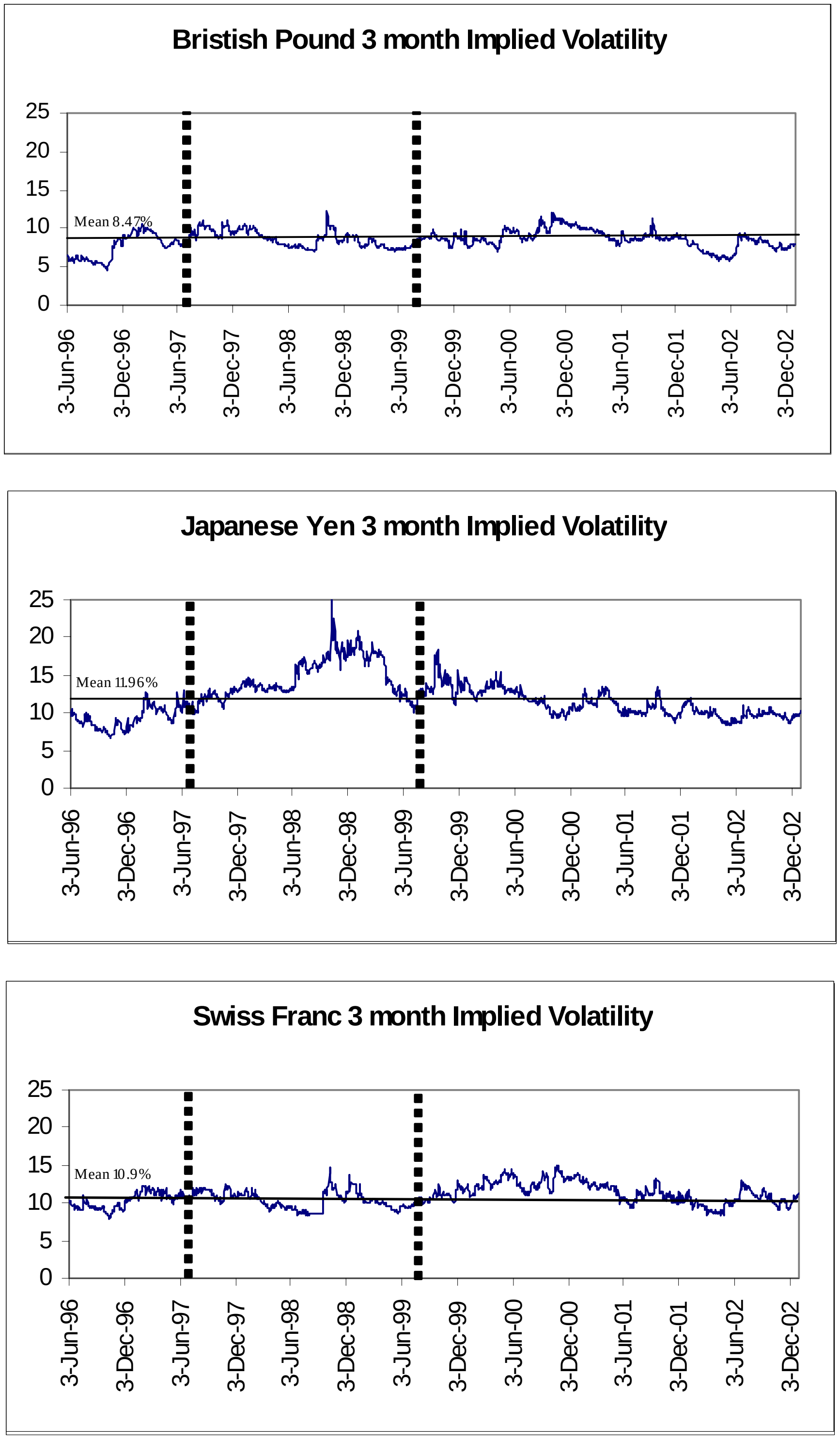

Figure 2: Time series plot of implied volatility quotes

This figure shows the daily implied volatility for the 3-month at-the-money straddle for the British Pound, the Japanese Yen and the Swiss Franc between June 1996 and December 2002. The two vertical dash lines indicate the start and the end of the Asian currency crisis period.

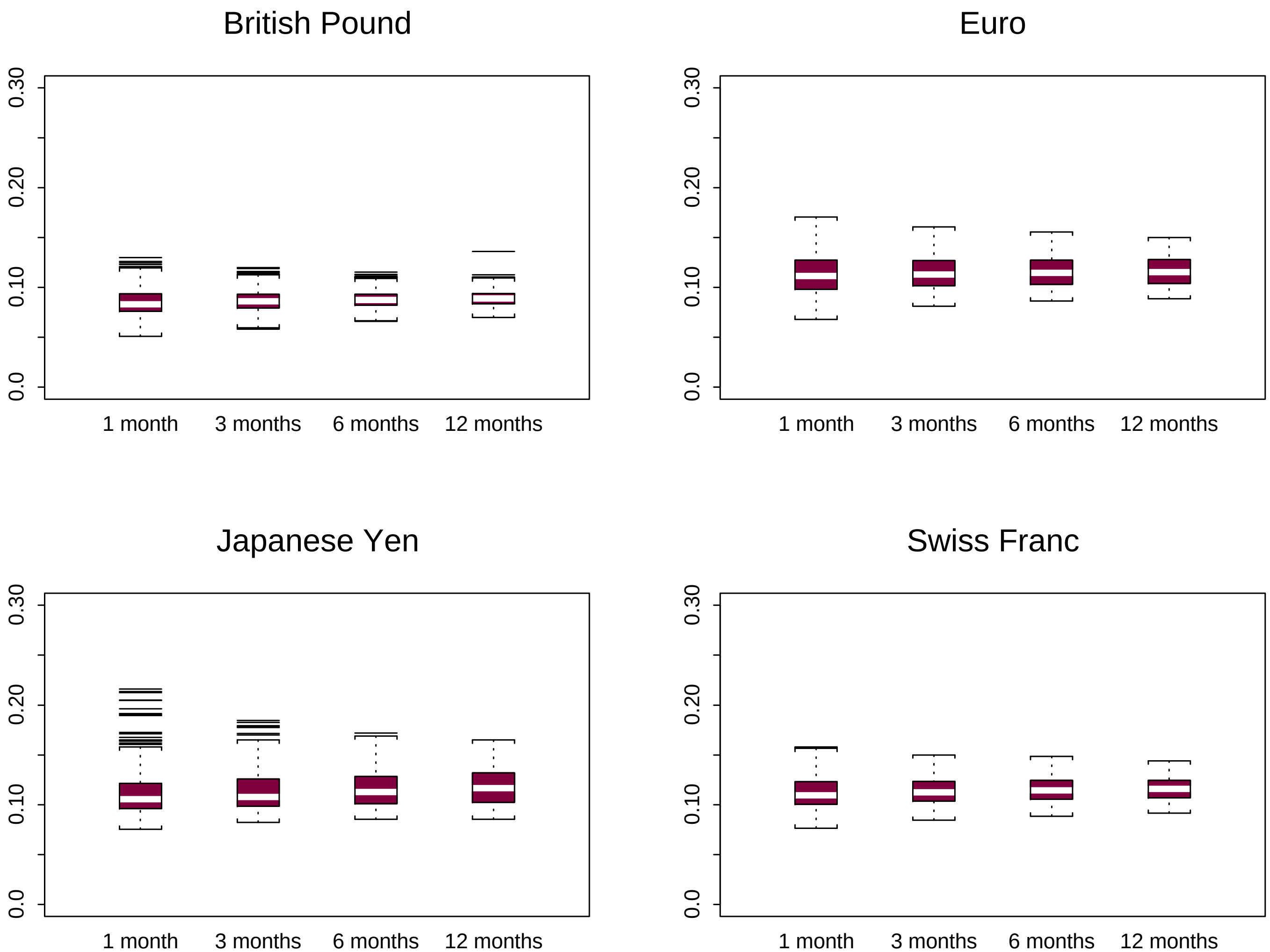

Figure 3: Distribution of implied volatility quotes in the post-Asian currency crisis sub-period
This figure shows the boxplots of the daily implied volatility quotes for 1-month, 3-month, 6-month and 12-month at-the-money straddle between July 1999 and December 2002 for all four currencies.