



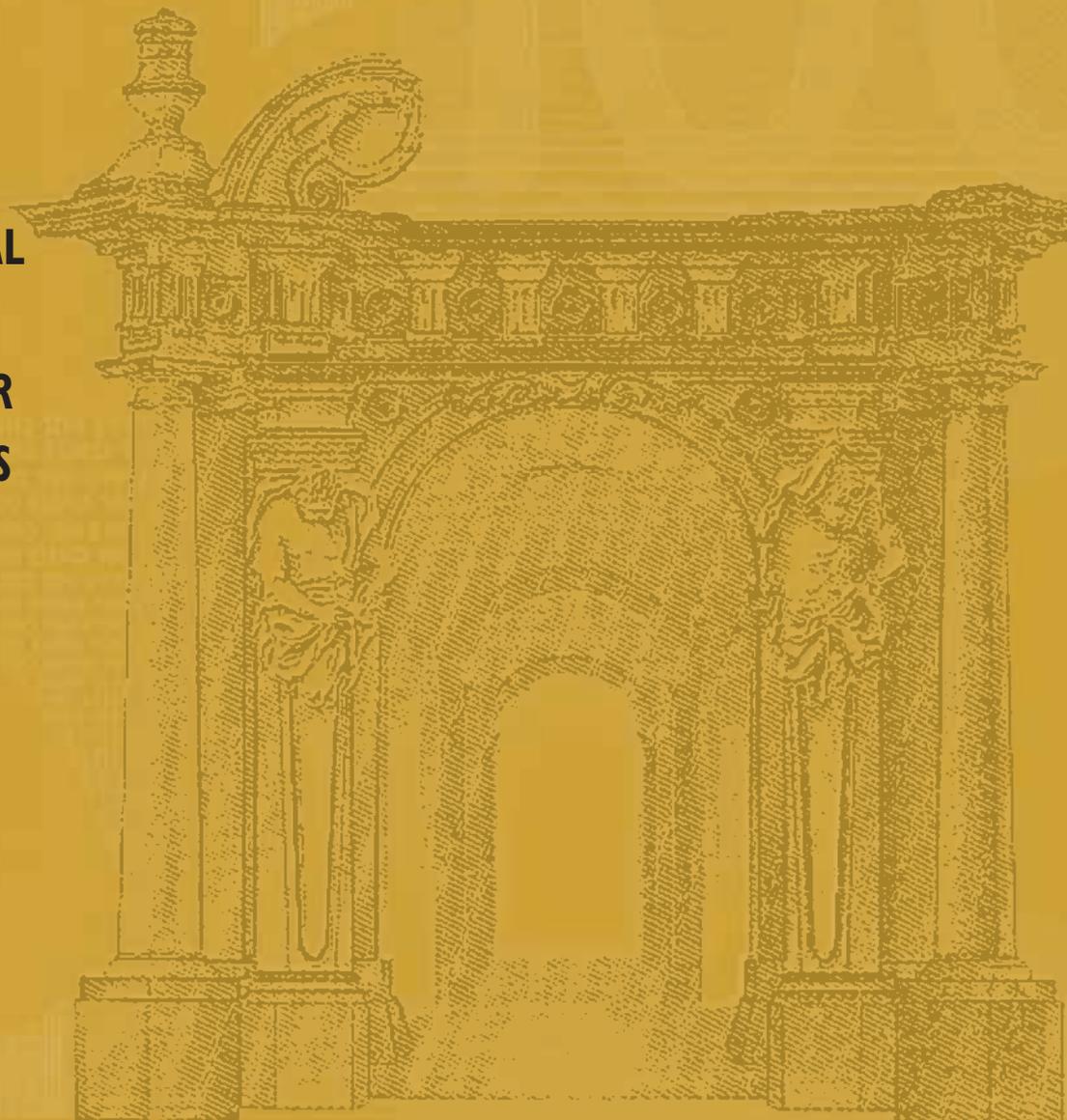
EUROPEAN CENTRAL BANK

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NO. 366 / JUNE 2004

**THE INFORMATIONAL
CONTENT OF
OVER-THE-COUNTER
CURRENCY OPTIONS**

by Peter Christoffersen
and Stefano Mazzotta





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by Peter Christoffersen²
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Abstract

Financial decision makers often consider the information in currency option valuations when making assessments about future exchange rates. The purpose of this paper is to systematically assess the quality of option based volatility, interval and density forecasts. We use a unique dataset consisting of over 10 years of daily data on over-the-counter currency option prices. We find that the OTC implied volatilities explain a much larger share of the variation in realized volatility than previously found using market-traded options. Finally, we find that wide-range interval and density forecasts are often misspecified whereas narrow-range interval forecasts are well specified.

JEL Classifications: G13, G14, C22, C53

Keywords: FX, Volatility, Interval, Density, Forecasting

Non-Technical Summary

Financial decision makers often consider the forward-looking information in currency option valuations when making assessments about future developments in foreign exchange rates. Option implied volatilities can be used as forecasts of realised volatility and interval and density forecasts can be extracted from strangles and risk-reversals. The purpose of this paper is to assess the quality of such volatility, interval and density forecasts. Our work is based on a very unique database consisting of more than ten years of daily quotes on European currency options from the OTC market. The OTC quotes include at-the-money implied volatilities, strangles and risk-reversals on the dollar, yen and pound per euro as well as on the yen per dollar. From this data we have constructed daily 1-month interval and density forecasts using the methodology in Malz (1997).

The main findings of the paper are as follows: First and foremost, we find that the OTC implied volatilities explain a much larger share of the variation in realized volatility than has been found previously in studies relying on market-traded options. Second, we find that wide-range interval forecasts are often misspecified whereas narrow-range interval forecasts are well specified. Third, we find that the option-based density forecasts are rejected in general. Graphical inspection of the density forecasts suggests that while the sources of rejections vary from currency to currency misspecification of the distribution tails is a common source of error.

Our paper contributes in two areas of the literature. First, to our knowledge, the empirical performance of option-based interval and density forecasts has not been systematically explored so far. Second, while there is a considerable literature on implied volatility forecasts from market-traded options, OTC data have only recently been employed.

One of our contributions consists of analyzing a unique dataset of OTC options which turns out to have impressive volatility prediction properties. OTC options are quoted daily with a fixed maturity (say one month) whereas market-traded options have rolling maturities which in turn complicate their use in fixed-horizon volatility forecasting.

In addition to volatility forecasts we evaluate option-based interval and density forecasts which are widely used by practitioners but which have not been systematically assessed so far. OTC options are quoted daily with fixed moneyness in contrast with market-traded options which have fixed strike prices and thus time-varying moneyness as the spot price changes. This time-varying moneyness complicates the use of market-traded options for interval and density forecasting in that the effective support of the distribution is changing over time. Finally, the

trading volume in OTC options is often much larger than in the corresponding market traded contracts which in turn is likely to render the OTC quotes more reliable for information extraction.

Several promising directions for future research exist. First, policy makers may be interested in assessing speculative pressures on a given exchange rate. The option implied densities can be used in this regard by constructing daily option-implied probabilities of say a 3% appreciation or depreciation during the next month. Second, the accuracy of the left and right tail interval forecast could be analyzed separately in order to gain further insight on the probability of a sizable appreciation or depreciation. Third, relying on the triangular arbitrage condition linking the JPY/EUR, the USD/EUR, and the JPY/USD, one can construct option implied covariances and correlations from the option implied volatilities. These implied covariances can then be used to forecast realized covariances as done for volatilities in Tables 1-4. Fourth, the misspecification found in the option-implied density forecasts may be rectified by assuming different tail-shapes in the density estimation or by incorporating return-based information. Converting the risk-neutral densities to their statistical counterparts may be useful as well but will require further assumptions, which may or may not be empirically valid. Bliss and Panigirtzoglou (2004) present promising results in this direction. Finally, one could consider making density forecasts combining option-implied and return based densities. We leave these important issues for future work.

1. Introduction

Financial decision makers often consider the forward-looking information in currency option valuations when making assessments about future developments in foreign exchange rates.¹ Option implied volatilities can be used as forecasts of realised volatility and interval and density forecasts can be extracted from strangles and risk-reversals. The purpose of this paper is to assess the quality of such volatility, interval and density forecasts. Our work is based on a very unique database consisting of more than ten years of daily quotes on European currency options from the OTC market.² The OTC quotes include at-the-money implied volatilities, strangles and risk-reversals on the dollar, yen and pound per euro³ as well as on the yen per dollar. From this data we have constructed daily 1-month interval and density forecasts using the methodology in Malz (1997).

The main findings of the paper are as follows: First and foremost, we find that the OTC implied volatilities explain a much larger share of the variation in realized volatility than has been found previously in studies relying on market-traded options. Second, we find that wide-range interval forecasts are often misspecified whereas narrow-range interval forecasts are well specified. Third, we find that the option-based density forecasts are rejected in general. Graphical inspection of the density forecasts suggests that while the sources of rejections vary from currency to currency misspecification of the distribution tails is a common source of error.

Several early contributions use market-based options data with mixed results. Beckers (1981) finds that not all available information is reflected in the current option price and questions the efficiency of the option markets. Canina and Figlewski (1993) find implied volatility to be a poor forecast of subsequent realized volatility. Lamoureux and Lastrapes (1993) provide evidence against restrictions of option pricing models which assume that variance risk is not priced. Jorion (1995) finds that statistical models of volatility based on returns are outperformed by implied volatility forecasts even when the former are given the advantage of ex post in sample parameter estimation. He also finds evidence of bias. More recently, Christensen and Prabhala (1998) using longer time series and non overlapping data find that implied volatility outperforms

¹ See for example Bank for International Settlements (2003), Bank of England (2000), International Monetary Fund (2002), and OECD (1999).

² The OTC volatilities used in this paper were provided by Citibank N.A

³ Prior to January 1, 1999 these were denoted in DEM.

past volatility in forecasting future volatility. Fleming (1998) finds that implied volatility dominates the historical volatility in terms of ex ante forecasting power and suggests that a linear model which corrects for the implied volatility's bias can provide a useful market-based estimator of conditional volatility. Blair, Poon, and Taylor (2001), find that nearly all relevant information is provided by the VIX index and there is not much incremental information in high-frequency index returns. Neely (2003) finds that econometric projections supplement implied volatility in out-of-sample forecasting and delta hedging. He also provides some explanations for the bias and inefficiency pointing to autocorrelation and measurement error in implied volatility.

In work concurrent with ours, Pong, Shackleton, Taylor and Xu (2004) find that high-frequency historical forecasts are superior to implied volatilities using OTC data for horizons up to one week. Covrig and Low (2003) use OTC data to find that quoted implied volatility subsumes the information content of historically based forecasts at shorter horizons, and the former is as good as the latter at longer horizons.

Our paper contributes in two areas of the literature. First, to our knowledge, the empirical performance of option-based interval and density forecasts has not been systematically explored so far. Second, while there is a considerable literature on implied volatility forecasts from market-traded options, OTC data have only recently been employed.

One of our contributions consists of analyzing a unique dataset of OTC options which turns out to have impressive volatility prediction properties. OTC options are quoted daily with a fixed maturity (say one month) whereas market-traded options have rolling maturities which in turn complicate their use in fixed-horizon volatility forecasting.

In addition to volatility forecasts we evaluate option-based interval and density forecasts which are widely used by practitioners but which have not been systematically assessed so far. OTC options are quoted daily with fixed moneyness in contrast with market-traded options which have fixed strike prices and thus time-varying moneyness as the spot price changes. This time-varying moneyness complicates the use of market-traded options for interval and density forecasting in that the effective support of the distribution is changing over time. Finally, the trading volume in OTC options is often much larger than in the corresponding market traded contracts which in turn is likely to render the OTC quotes more reliable for information extraction.

The remainder of the paper is structured as follows. Section 2 defines the competing volatility forecasts we consider and describes the standard regression-based framework for

volatility forecast evaluation. Section 3 presents results on the option-implied and historical return-based volatility forecasts of realized volatility. Section 4 suggests a method for evaluating interval forecasts from option prices and present results from this method. Section 5 suggests methods for evaluating density forecasts from option prices and present results from these methods. Finally, Section 6 discusses potential points for future research.

2. Volatility Forecast Evaluation

In order to evaluate the informational content of the volatilities implied from currency options, we define the realized⁴ future volatility for the next h days to be

$$\sigma_{t,h}^{RV} = \sqrt{\frac{252}{h} \sum_{i=1}^h R_{t+i}^2}$$

in annualized terms, where $R_{t+i} = \ln(S_{t+i}/S_{t+i-1})$ is the FX spot return on day $t+i$. This realized volatility (and its logarithm) will be our forecasting object of interest in this section.⁵

We will consider four competing forecasts of realized volatility. First and most importantly the implied volatility from at-the-money OTC currency options with maturity h , where h is either 1 month or 3 months corresponding to roughly 21 and 63 trading days respectively. Denote this options-implied volatility by $\sigma_{t,h}^{IV}$.

The other three volatility forecasts are derived from historical FX returns only. The simplest possible forecast is the historical h -day volatility, defined as

$$\sigma_{t,h}^{HV} = \sqrt{\frac{252}{h} \sum_{i=1}^h R_{t-h+i}^2} = \sigma_{t-h,h}^{RV}$$

The historical volatility is a simple equal weighted average of past squared returns.

We can instead consider volatilities that apply an exponential weighting scheme putting progressively less weight on distant observations. The simplest such volatility is the Exponential Smoother or RiskMetrics volatility, where daily variance evolves as

$$\tilde{\sigma}_{t+1}^2 = (1-\lambda) \sum_{i=1}^{\infty} \lambda^{i-1} R_{t-i+1}^2 = \lambda \tilde{\sigma}_t^2 + (1-\lambda) R_t^2$$

⁴ See Andersen, T., T. Bollerslev, F. X. Diebold, and P. Labys, 2003.

⁵ Later on we will consider realized volatilities calculated from 30-minute rather than daily returns.

Following JP Morgan we simply fix $\lambda=0.94$ for all the daily FX returns. The fact that the coefficients on past variance and past squared returns sum to one makes this model akin to a random walk in variance. The annualized forecast for h -day volatility is therefore simply

$$\sigma_{t,h}^{RM} = \sqrt{252\tilde{\sigma}_{t+1}^2}$$

Finally we consider a simple, symmetric GARCH(1,1) model, where the daily variance evolves as

$$\hat{\sigma}_{t+1}^2 = \omega + \beta\hat{\sigma}_t^2 + \alpha R_t^2$$

In contrast with the RiskMetrics model, the GARCH model implies a non-constant term structure of volatility. The unconditional variance in the model can be computed as

$$\hat{\sigma}^2 = \frac{\omega}{1 - \alpha - \beta}$$

The conditional variance for day $t+h$ can be derived as

$$\hat{\sigma}_{t+h|t}^2 = \hat{\sigma}^2 + (\alpha + \beta)^{h-1}(\hat{\sigma}_{t+1}^2 - \hat{\sigma}^2)$$

And the annualized GARCH volatility forecast for day $t+1$ through $t+h$ is thus

$$\sigma_{t,h}^{GH} = \sqrt{\frac{252}{h} \sum_{i=1}^h \hat{\sigma}^2 + (\alpha + \beta)^{i-1}(\hat{\sigma}_{t+1}^2 - \hat{\sigma}^2)}$$

The GARCH model will have a downward sloping volatility term structure when the current variance is above the long horizon variance and vice versa.⁶

Notice that while we take the standard approach of estimating a daily volatility model to forecast monthly and quarterly volatility, this is not the only way to proceed. Ghysels, Santa-Clara and Valkanov (2003) have recently explored ways to estimate volatility forecasting models directly on the relevant horizon of interest. Rather than estimating say a monthly forecasting model on monthly data they make use of the information in daily observations in a horizon-specific forecasting model imposing a parsimonious lag structure on the daily observations.

Figure 1 shows the spot rates of the four FX rates analysed in this paper. Prior to the euro introduction in 1999 we observe FX options denoted against the Deutschmark (DEM) and we

⁶ The GARCH model contains parameters which must be estimated. We do this on rolling 10-year samples starting in January 1982 and using QMLE. Each year we forecast volatility one-year out-of-sample before updating the estimation sample by another calendar year of daily returns. The euro volatility forecasts are constructed using synthetic euro rates in the period prior to the introduction of the euro.

will therefore work with the DEM spot rates prior to the euro introduction as well. Prior to January 1, 1999 we use DEM options to forecast DEM volatility and afterwards we use euro options to forecast euro volatility.

The five volatility specifications including the realized volatility are plotted in Figures 2-5. Each page corresponds to a particular volatility specification and each column on a page represents an FX rate. The top row shows the 1-month volatility and the bottom row the 3-month volatility. Notice that the RiskMetrics volatilities in Figure 4 are identical for 1-month and 3-month maturities as the random-walk nature of this specification implies a flat volatility term structure.

We are now ready to assess the quality of the different volatility forecasts. This will be done in simple linear predictability regressions. We first run four univariate regressions for each currency

$$\sigma_{t,h}^{RV} = a + b\sigma_{t,h}^j + \varepsilon_{t,h}^j, \text{ for } j = IV, HV, RM, GH$$

The purpose of these univariate regressions is to assess the fit through the adjusted R^2 and to check how close the estimates of a are to 0 and how close the estimate of b are to 1. Bollerslev and Zhou (2003)⁷ point out that if the volatility risk is priced in the options markets then we should expect to find a positive intercept and a slope less than one in the above regression. In a standard stochastic volatility set up, it can be shown that if the price of volatility risk is zero, the process followed by the volatility is identical under the objective and the risk neutral measures. In such a case there would be no bias. However, the volatility risk premium is generally estimated to be negative which in turn implies that the volatility process under the risk neutral measure will have higher drift. This is also consistent with the fact that implied volatilities are empirically found to be upward biased estimates of the objective volatility.

Aside these considerations, for someone using implied volatility in the real time monitoring of FX movements, the intercept and slope coefficients are informative of the size of the bias and efficiency respectively of the forecasts.

In addition we will run three bivariate regressions including the implied volatility forecast as well as each of the three return-based volatility forecasts in turn. Thus we have

$$\sigma_{t,h}^{RV} = a + b\sigma_{t,h}^{IV} + c\sigma_{t,h}^j + \varepsilon_{t,h}^{IV,j}, \text{ for } j = HV, RM, GH$$

⁷ See also Bandi and Perron (2003), Chernov (2003), Bates (2002), and Benzoni (2001).



The purpose of the bivariate regressions is to assess if the return-based volatility forecasts add anything to the market-based forecasts implied from currency options.

Finally, we run a regression including all the four volatility forecasts in the same equation. The purpose of this regression is to assess the relative merits of the different volatility forecasts.

We will run all regressions for $h=21$ and 63 corresponding to the 1-month and 3-month option maturities. We will also run all regressions in levels of volatility as above as well as in logarithms. Due to the volatilities being strictly positive, the log specification may have error terms, which are better behaved than those from the level regressions.

3. Volatility Forecast Evaluation Results

Tables 1 and 2 report the regression point estimates as well as standard errors corrected for heteroskedasticity and autocorrelation. Throughout this paper we apply GMM using the Newey-West⁸ weighting matrix with a prespecified bandwidth equal to 21 days for the 1-month horizon (Table 1) and 63 days for the 3-month horizon (Table 2). The bandwidth is chosen as to eliminate the influence of the autocorrelation induced by the overlapping observation. We also report the regression fit using the adjusted R^2 .

Several strong and interesting empirical regularities emerge. First, the regression fit is very good in all cases. Jorion (1995) reports R^2 in the region 0.10-0.15 for the USD/JPY, USD/DEM and USD/CHF using implied volatility forecasts. We get instead R^2 of 0.30-0.38 for the 1-month maturity and 0.16-0.35 for the 3-month maturity case. Second, comparing the R^2 across the univariate forecast regressions we see that the implied volatility is the best volatility forecast. This result holds across currencies and horizons.

Third, comparing the slope estimates across the bivariate forecast regressions where the implied volatility forecast is included along with each of the other three forecasts, the implied volatility always has the highest slope. Thus, in the cases when GARCH has a higher slope in the univariate regression the bivariate regressions including the IV and GARCH forecasts always assign a larger slope to the IV forecast. The fact that GARCH-based forecasts sometimes have a slope closer to one than do the implied volatility forecasts is not surprising given the price of

⁸ See Newey and West (1987).

volatility risk argument in Bollerslev and Zhou (2003) and others.⁹ Nevertheless, it is interesting to note that the R^2 is higher for the implied volatility forecasts even in the cases where its slope is lower than that of the GARCH-based forecasts.

Fourth, comparing the slope estimates across the multivariate forecast regressions where all four forecasts are included simultaneously the implied volatility has the highest slope. This result holds across currencies and horizons. Fifth, comparing across the horizon forecasts it appears perhaps not surprisingly that the 1-month forecasts have higher R^2 than the 3-month forecasts. Finally, the slope coefficient is often insignificantly different from one for the IV forecasts, and its intercept is often insignificantly different from zero.

Tables 3 and 4 contain the same set of regressions as Tables 1 and 2, but now run on the euro sample (i.e. post January 1, 1999) only, and furthermore relying on 30-minute intraday returns rather than daily returns to compute the one and three month realized volatilities. We also report the euro sample estimates using daily data in Table 3a and 4a.

The objective of Tables 3 and 4 is to see if the post-euro sample is different from the full sample period which straddles the introduction, and furthermore to assess the value of using high-frequency returns in volatility forecast evaluation. The theoretical benefits of doing so have been documented in Andersen and Bollerslev (1998) and Andersen, Bollerslev and Meddahi (2003) who show that the R^2 in the regressions we run will be significantly higher when proxying for true volatility using an intraday rather than daily return-based volatility measure. As pointed out by Alizadeh, Brandt and Diebold (2002), and Brandt and Diebold (2003) this theoretical benefit may in practice be outweighed by market microstructure noise, but relying on 30-minutes returns in very liquid markets as we do here should mitigate these problems.

The results in Table 3 and 4 are broadly similar to those from the full sample but using high-frequency returns does lead to some new interesting findings. First, for the three euro cross currencies the regression fit is typically much better now. Due to the obvious structural break in 1999 this is perhaps not surprising. But it is still interesting that we now get R^2 as high as 65% in the univariate regressions. Note that the R^2 for the 3-month JPY/USD case is now slightly lower than before. It is therefore not simply the case the FX volatility has become more predictable as of late.

⁹ Whether volatility risk is priced is of course an empirical question: some of our results indirectly support the conjecture that volatility risk is priced in the currency options markets.

Second, comparing the R^2 across the univariate forecast regressions the implied volatility is typically the best volatility forecast.¹⁰ The exception is the EUR/JPY rate. Third, comparing the slope estimates across the bivariate and multivariate forecast regressions the implied volatility typically has the highest slope. It is interesting that the simple historical realized volatility forecast now sometimes has the highest slope.¹¹ This is results is exclusively due to the use of high frequency data as it is easy to infer from the comparison of Table 3-4 to 3a-4a. The added accuracy in this forecast from the intra-day returns is thus evident.

In order to give assess the importance of the choice of estimation period we have also run the same regressions using in sample GARCH estimates.¹² Although the explanatory power as measured by the adjusted R^2 of the in sample GARCH is substantially higher compared to that of the out of sample regressions, in most cases the change does not affect the results in the 1-month regressions for any currency both in the full sample and in the post 1999 sample. The same is true for the 3-month horizon with the only exception of the GBP in the full sample: here the in sample GARCH get the highest coefficient in the multivariate regression.

In summary, we find strong evidence that the implied volatility from FX options is useful in predicting future realized volatility at the one and three month horizons. The predictability is particularly strong for the euro cross rates in the recent period. In spite of the potential bias from volatility risk being priced in the options, the regression slope on the volatility forecasts are often quite close to one.

Perhaps the most striking finding in Tables 1-4 is the high level of R^2 found in the implied volatility regressions. It appears that the volatility implied in the OTC options offer much more precise forecasts than the volatility implied from market-traded options, which have been analyzed in previous studies. We suspect that the so-called telescoping bias arising from the rolling-maturity structure of market-traded options (see Christensen, Hansen, and Prabhala, 2001) could be part of the reason. Furthermore, the fact that OTC options are quoted daily with a fixed moneyness, as opposed to a fixed strike price, which ensures that the options used for

¹¹ The historical volatility forecast could potentially be improved further by estimating a slope coefficient thus allowing for mean reversion in the forecast.

¹² Results are not shown here to conserve space.

volatility forecasting are exactly at-the-money each day. Finally, the large volume of transaction in OTC currency options compared with market traded options may offer additional explanation.

4. Interval Forecast Evaluation

The information in currency options may be useful not only for volatility forecasting but for spot rate distribution forecasting more generally. In the following sections we abstract from the difference between risk neutral and objective distributions. The empirical question we want to ask is: “How well can risk neutral intervals and densities computed using standard methodologies forecast physical interval and densities?”. The legitimacy of the question stems from the fact that financial decision makers often consider the information in currency option valuations when making assessments about future exchange rates without worrying about this important theoretical difference. In addition, this pragmatic approach can be justified by considering that for currencies the risk premium, i.e. the conditional mean, which would largely determine the difference between risk neutral and physical, may not be as important as the higher order moments and particularly the conditional variance.¹³ In other words, the tests in the following sections can be considered as joint tests of the methodology used to extract densities and intervals under the additional hypothesis that the objective and risk neutral distributions are not very different.¹⁴

These tests may have low power with respect to generic alternative hypotheses but they can help assessing whether certain specific pieces of information have been duly taken into account in the construction of these intervals and densities. Rejection may come from the presence of some currency risk premium: this situation will shift apart the mean under the two probabilistic measures. Rejection could also come from methodological and data shortcoming in the construction of the interval and densities: this is likely to be the case for the widest intervals and the tails of the distributions when they are based on the extrapolation of market data.

¹³ It is also the case that there is no methodology to transform risk neutral distributions into their objective counterparts without making several, possibly very restrictive assumptions.

¹⁴ In order to save space we do not compare the predictive performance of our option implied densities with that of densities based on historical FX returns only. This is an interesting exercise which we leave for future studies.

In substance, the results of these tests should be seen as suggestion for improvement of the prevalent methodologies and caveats with regard to how much trust should one put in these forecasts.

In this section we study the performance of one-month interval forecasts calculated from option prices and forward rates.

The intervals are constructed from the option-implied densities which in turn are calculated using the estimation method in Malz (1997). The Malz methodology is based on a second order Taylor approximation to the volatility smile. The procedure forces the approximation of the implied volatility function to be exactly equal to the observed implied volatility for the three values of the Black-Scholes delta, namely .25, .50, and .75. It uses this interpolated approximation of the smile to compute a continuous option price function. It then uses the classical result in Breeden and Litzenberger (1978) to compute the risk neutral density.

We have computed conditional interval forecasts for the {0.45, 0.55} probability interval, as well as the {0.35, 0.65}, {0.25, 0.75}, {0.15, 0.85}, and the {0.05, 0.95} intervals. These forecasts are shown in Figure 6. Notice that the intervals for the GBP/DEM look excessively jagged in a large part of the pre euro sample.

We now set out to evaluate the usefulness of the interval forecasts following the methodology developed first in Christoffersen (1998). Let the generic interval forecast be defined as

$$\{L_{t,h}(p_L), U_{t,h}(p_U)\}$$

where p_L and p_U are the percentages associated with the lower and upper conditional quantiles making up the interval forecast.

Consider now the indicator variable defined as

$$I_{t,h} = \begin{cases} 0, & \text{if } S_{t+h} \in \{L_{t,h}(p_L), U_{t,h}(p_U)\} \\ 1, & \text{if not} \end{cases}$$

Then if the interval forecast is correctly calibrated, we must have that

$$E[I_{t,h} | X_t] = 1 - (p_U - p_L) \equiv p$$

where X_t denotes a vector of information variables (and functions thereof) available on day t . If the interval forecast is correctly calibrated then the expected outcome of the future FX rate

falling outside the predicted interval must be a constant equal to the pre-specified interval probability p .

This hypothesis will be tested in a linear regression setup, but binary regression methods could have been used as well. Under the alternative hypothesis we have

$$I_{t,h} - p = a + bX_t + \varepsilon_{t,h}$$

and the null hypothesis corresponds to the restrictions

$$a = b = 0$$

Running these regressions on daily data we again have to worry about overlapping observations, which we allow for using GMM estimation.

Table 5 shows the results for the regression-based tests of the interval forecasts. The interval forecasts for the $\{0.45, 0.55\}$, $\{0.35, 0.65\}$, $\{0.25, 0.75\}$, $\{0.15, 0.85\}$, and the $\{0.05, 0.95\}$ intervals are denoted by the probability of an observation outside the interval, i.e. $p=.90$, $.70$, $.50$, $.30$ and $.10$ respectively. We refer to these outside observations as hits. The zero/one hit sequence (less its expected value p) is regressed on a constant, the 21-day lagged hit and the 21-day lagged 1-month implied volatility. The lagged hit is included to capture any dependence in the outside observations. The implied volatility is included to assess if it is incorporated optimally in the construction of the interval forecast. If the interval forecast is correctly specified then the intercept and slopes should all be equal to zero. Table 5 reports coefficient estimates along with t -statistics again calculated using GMM. Below the solid line in each subsection of the table the average hit rate, which should be equal to p , is reported along with the t -statistic from the test that the average hit rate indeed equals p . All t -statistics larger than two in absolute value are denoted in boldface type. We also include Wald tests of the joint hypothesis that all the estimated coefficients are zero.

The results in Table 5 can be summarized as follows. First, for the pound the average hit rate is significantly different from the pre-specified p for all but the narrowest interval (with outside probability equal to $.90$). The jagged pound intervals evident from Figure 6 are probably the culprit here. Second, for the other three FX rates, the average hit rate is typically not significantly different from the pre-specified p . The only notable exception is the wide-range intervals (with outside probability $.10$) where all but the JPY/EUR intervals are rejected. It thus appears that the interval forecast have the hardest time forecasting the tails of the spot rate distribution.

Third, notice that no regression slopes are significant in the JPY/EUR case. No dependence in the hit sequence is apparent and the information in implied volatilities seems to be used optimally in this case. Fourth, while the interval forecasts for the JPY/EUR are well specified, the intervals for the other three forecasts are typically rejected. The slope on the 21-days lagged implied volatility is most often found to be significantly negative. This indicates that the hits tend to occur when the implied volatility was relatively low on the day the forecast was made. If the intervals had been using the implied volatility information optimally then no dependence should be found between the current implied volatility and the subsequent realization of the hit sequence.

Table 6 reports the interval forecast evaluation results using data from the euro sample only. The results are now somewhat different and can be summarized as follows. First, the average hit rate is typically not significantly different from the pre-specified p with a couple of noteworthy exceptions: The average hit rate is rejected across all the four FX rates for the widest intervals. Again, it appears that the option implied densities have trouble capturing the tails of the distribution. For all four FX rates it is the case that the outside hit frequency is lower than it should be, thus the wide-range option-implied intervals are too wide on average.

Second, the average hit rate is rejected in the two widest intervals for the pound, but in general the pound intervals are better calibrated in the euro sample than before. Third, the JPY/USD interval is now the most poorly calibrated interval.

In summary we find that the option-implied interval forecast for the euro cross rates perform well in the post January 1, 1999 sample. The exception is the forecasts for the widest intervals, which tend to be too wide on average. The option-implied densities apparently have trouble capturing the tail behaviour of the spot rate distributions. The rejection of widest intervals and thus misspecification of the tails of the density forecasts should perhaps not come as a surprise. The density tails are estimated on the basis of an extrapolation of the volatility smile from the values for which option price information is available (that is for deltas equal to .25, .50, and .75). It appears that this extrapolation could be improved. We will pursue the topic of density forecasting in more detail in the next section.

5. Density Forecast Evaluation

The option-implied interval forecasts analyzed above are constructed from the implied density, which contains much more information than the intervals alone. We would therefore like

to evaluate the appropriateness of these density forecasts in their own right. Doing so is likely to yield some insights into the poor performance of the widest interval forecasts, which was noted above. We start off by outlining the general ideas behind density forecast evaluation developed by Diebold, Gunther and Tay (1998).

Let $F_{t,h}(S)$ and $f_{t,h}(S)$ denote the cumulative and probability density function forecasts made on day t for the FX spot rate on day $t+h$. We can then define the so-called probability transform variable as

$$U_{t,h} \equiv \int_{-\infty}^{S_{t+h}} f_{t,h}(u) du \equiv F_{t,h}(S_{t+h}).$$

The transform variable captures the probability of obtaining a spot rate lower than the realization where the probability is calculated using the density forecast. The probability will of course take on values in the interval $[0,1]$. If the density forecast is correctly calibrated then we should not be able to predict the value of the probability transform variable $U_{t,h}$ using information available at time t . That is we should not be able to forecast the probability of getting a value smaller than the realization. Moreover, if the density forecast is a good forecast of the true probability distribution then the estimated probability will be uniformly distributed on the $[0,1]$ interval.

5.a Graphical Density Forecast Evaluation

Figure 7 assesses the unconditional distribution of the probability transform variable $U_{t,h}$ for each spot rate through a simple histogram. If the density forecast is correctly calibrated then each of the histograms should be roughly flat and a random 10% of the 31 bars should fall outside the two horizontal lines delimiting the 90% confidence band.

It appears that the histograms display certain systematic differences from the uniform distribution. Notice in particular that the JPY/EUR histogram (top right panel) shows a systematically declining shape moving from left to right. This is indicative of the forecasted mean spot rate being wrong. There are too many observations where the realized spot rate lies in the left side of the forecasted distribution (and generates a $U_{t,h}$ less than 0.5) and vice versa. In the USD/EUR case (top left panel) it appears that there are not enough observations in the two extremes, which suggests that the forecasted density has tails, which are too fat. This finding matches Table 5 where we found that the widest intervals were too wide for the USD/EUR. Finally, the JPY/USD distribution (bottom right panel) appears to be misspecified in the right tail.

For certain purposes, including statistical testing, it is more convenient to work with normally distributed rather than uniform variables for which the bounded support may cause technical difficulties. As suggested by Berkowitz (2001)¹⁵ we can use the standard normal inverse cumulative density function to transform the uniform probability transform to a normal transform variable

$$Z_{t,h} = \Phi^{-1}(U_{t,h}) = \Phi^{-1}(F_{t,h}(S_{t+h}))$$

If the implied density forecast is to be useful for forecasting the physical density, it must be the case that the distribution of $U_{t,h}$ is uniformly distributed and independent of any variable X_t observed at time t . Consequently the normal transform variable must be normally distributed and also independent of all variables observed at time t .

Figure 8 assesses the unconditional normality of the normal transforms by plotting the histograms with a normal distribution superimposed.¹⁶ The normal histograms typically confirm the findings in Figure 7 but also add new insights. While it appeared in Figure 7 that the GBP/EUR had fairly random deviations from the uniform distribution, it now appears that the normal transform is systematically skewed compared with the superimposed normal distribution.

While the graphical evidence in Figures 7 and 8 is quite informative of the potential deficiencies in the option implied density forecasts, it may be interesting to formally test the hypothesis of the normal transforms following the standard normal distribution. We do this below.

5.b Tests of the Unconditional Normal Distribution

We first want to test the simple hypothesis that the normal transform variables are unconditionally normally distributed. Basically, we want to test if the histograms in Figure 8 are significantly different from the superimposed normal distribution. The unconditional normal hypothesis can be tested using the first four moment conditions

$$E[Z_{t,h}] = 0, \quad E[Z_{t,h}^2] = 1, \quad E[Z_{t,h}^3] = 0, \quad E[Z_{t,h}^4] = 3$$

¹⁵ See also Diebold, Hahn and Tay (1999).

¹⁶ The superimposed normal distribution functions have different heights due to the different number of observations available for each currency.

We still need to allow for autocorrelation arising from the overlap in the data and so we estimate the following simply system of regressions

$$\begin{aligned}Z_{t,h} &= a_1 + \varepsilon_{t,h}^{(1)} \\ Z_{t,h}^2 - 1 &= a_2 + \varepsilon_{t,h}^{(2)} \\ Z_{t,h}^3 &= a_3 + \varepsilon_{t,h}^{(3)} \\ Z_{t,h}^4 - 3 &= a_4 + \varepsilon_{t,h}^{(4)}\end{aligned}$$

using GMM and test that each coefficient is zero individually as well as the joint test that they are all zero jointly.¹⁷ In each case we allow for 21 day overlap in the daily observations. The results of these tests are reported in Tables 7 and 8. Table 7 tests for unconditional normality on the entire sample and Table 8 restricts attention to the post 1999 period.

Table 7 shows that while only a few of the individual moments are found to be significantly different from the normal counterpart, the joint (Wald) test that all moments match the normal distribution is rejected strongly in three cases and weakly in the case of the JPY/USD. The post 1999 results are very similar. Now the Wald test strongly rejects all four density forecasts. We thus find fairly strong evidence overall to reject the option-implied density forecasts using simple unconditional tests.

In order to focus attention on the performance of the density forecasts in the tails of the distribution, we report QQ-plots of the normal transform variables in Figure 9. QQ-plots display the empirical quantile of the observed normal transform variable against the theoretical quantile from the normal distribution. If the distribution of the normal transform is truly normal then the QQ-plot should be close to the 45-degree line.

Figure 9 shows that the left tail is fit poorly in the case of the dollar, and that the right tail is fit poorly in the case of the pound and the JPY/USD. In the case of the dollar there are too few small observations in the data, which is evidence that the option implied density has a left tail that is too thick. The pound has too many large observations indicating that the right tail of the density forecast is too thin. In the JPY/USD case the right tail appears to be too thick. These findings are also evident from Figure 7.

Rejecting the unconditional normality of the normal transform variables is of course important, but it does not offer much constructive input into how the option-implied density

¹⁷ See Bontemps and Meddahi (2002) for related testing procedures.

forecasts can be improved upon. The conditional normal distribution testing we turn to now is more useful in this regard.

5.c Tests of the Conditional Normal Distribution

We would like to know why the densities are rejected, and specifically if the construction of the densities from the options data can be improved somehow. To this end we want to conduct tests of the *conditional* distribution of the normal transform variable. Is it possible to predict the realization of the time $t+h$ normal transform variable using information available at time t ? If so then this information is not used optimally in the construction of the density forecast.

The conditional hypothesis can be tested using the generic moment conditions

$$E[Z_{t,h}f_1(X_t)] = 0, \quad E[Z_{t,h}^2f_2(X_t)] = 1, \quad E[Z_{t,h}^3f_3(X_t)] = 0, \quad E[Z_{t,h}^4f_4(X_t)] = 3$$

Choosing particular moment functions and variables these conditions can be implemented in a regression setup as follows

$$\begin{aligned} Z_{t,h} &= a_1 + b_{11}Z_{t-h,h} + b_{12}\sigma_t^{IV} + \varepsilon_{t,h}^{(1)} \\ Z_{t,h}^2 - 1 &= a_2 + b_{21}Z_{t-h,h}^2 + b_{22}(\sigma_t^{IV})^2 + \varepsilon_{t,h}^{(2)} \\ Z_{t,h}^3 &= a_3 + b_{31}Z_{t-h,h}^3 + b_{32}(\sigma_t^{IV})^3 + \varepsilon_{t,h}^{(3)} \\ Z_{t,h}^4 - 3 &= a_4 + b_{41}Z_{t-h,h}^4 + b_{42}(\sigma_t^{IV})^4 + \varepsilon_{t,h}^{(4)} \end{aligned}$$

where we include the lagged power of the normal transform as well as the power of the current implied volatility as regressors. We can now test that the regression coefficients are zero.

Table 9 shows the estimation results of the regression systems for the four exchange rates. In line with previous results we find that the information in the implied volatility is not used optimally in the construction of the option-implied density forecast for the GBP/EUR.

Table 10 shows the regressions from Table 9 run only on the euro sample. Comparing the two tables, it is evident that the clear rejection of the pound density forecasts in Table 9 is largely due to problems in the pre-euro sample. Restricting attention to the euro sample there is more evidence on the implied volatility being misspecified in the JPY/USD rate. Looking across Tables 9 and 10 we see that the Wald test of all coefficients being zero is strongly rejected for all four FX rates in both samples. It would therefore seem possible in general to improve upon the option-implied density forecasts studied here.

6. Conclusion and Directions for Future Work

We have presented evidence on the usefulness of the information in over-the-counter currency option for forecasting various aspects of the distribution of exchange rate movements. We focused on three aspects of spot rate forecasting, namely, volatility forecasting, interval forecasting, and distribution forecasting. While other papers have pursued volatility forecasting in manners similar to ours we believe to be the first to systematically investigate the properties of option-based interval and density forecasts. Furthermore, we are some of the first to investigate long time series of volatilities from over-the-counter options, which we find to be much more useful for volatility forecasting than the market-traded options used in previous studies. The reasons for this important finding are likely to be 1) the so-called telescoping bias arising from rolling maturities in market-traded options is not an issue in the OTC options, 2) the time-varying moneyness in market-traded options, and 3) the volume of trades done over-the-counter is much larger than the exchange trading volume for currency options.

Our other findings can be summarized as follows. First, the implied volatilities from currency options typically offer predictions that explain much more of the variation in realized volatility than do volatility forecasts based on historical returns only. This ranking is however sometimes reversed when historical volatility forecasts are constructed from intraday returns. Second, when combining implied volatility forecasts with return-based forecasts, the latter typically receive very little weight. Third, in terms of interval forecasting on the entire 1992-2003 sample, the option-implied intervals are useful for the JPY/EUR but rejected for the other three currencies in the study. Fourth, focusing on the euro sample, the option-implied interval forecasts are generally useful. Two notable exceptions are the widest-range intervals with 90% coverage and the JPY/USD intervals in general. The 90% intervals tend to be too wide due to the misspecification of the tails of the forecast distribution. Fifth, when evaluating the entire implied density forecasts these are generally rejected. The graphical evidence again suggests that the tails in the distribution are typically misspecified. We thus conclude that the information implied in option pricing is useful for volatility forecasting and for interval forecasting as long as the interest is confined to intervals with coverage in the 10-70% range.

The rejection of the widest intervals and the complete density forecast is of course interesting and warrants further scrutiny. The potential reasons are at least fourfold. First, the option contracts used may not have extreme enough strike prices to be useful for constructing accurate distribution tails. Second, the information in options could be used sub-optimally in the

density estimates. Third, we could be rejecting the densities because certain information available at the time of the forecasts is not incorporated in the option prices used to construct the densities, i.e. option market inefficiencies. Fourth, the risk premium considerations, which were abstracted from in this paper could be important enough to reject the risk-neutral density forecasts considered. The misspecification of the mean in the case of the JPY/EUR rate suggests that an omitted risk premium could be the culprit in that case. For the other three currencies, however, Figure 9 suggests that the culprit is tail misspecification, which is likely to arise from the lack of information on deep in-the-money and deep out-of-the-money options.

We round off the paper by listing some promising directions for future research. First, policy makers may be interested in assessing speculative pressures on a given exchange rate. The option implied densities can be used in this regard by constructing daily option-implied probabilities of say a 3% appreciation or depreciation during the next month. Second, the accuracy of the left and right tail interval forecast could be analyzed separately in order to gain further insight on the probability of a sizable appreciation or depreciation. Third, relying on the triangular arbitrage condition linking the JPY/EUR, the USD/EUR, and the JPY/USD, one can construct option implied covariances and correlations from the option implied volatilities. These implied covariances can then be used to forecast realized covariances as done for volatilities in Tables 1-4. Fourth, the misspecification found in the option-implied density forecasts may be rectified by assuming different tail-shapes in the density estimation or by incorporating return-based information. Converting the risk-neutral densities to their statistical counterparts may be useful as well but will require further assumptions, which may or may not be empirically valid. Bliss and Panigirtzoglou (2004) present promising results in this direction. Finally, one could consider making density forecasts combining option-implied and return based densities. We leave these important issues for future work.

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Figure 1: Foreign Exchange Spot Rates, Pre and Post Euro Introduction

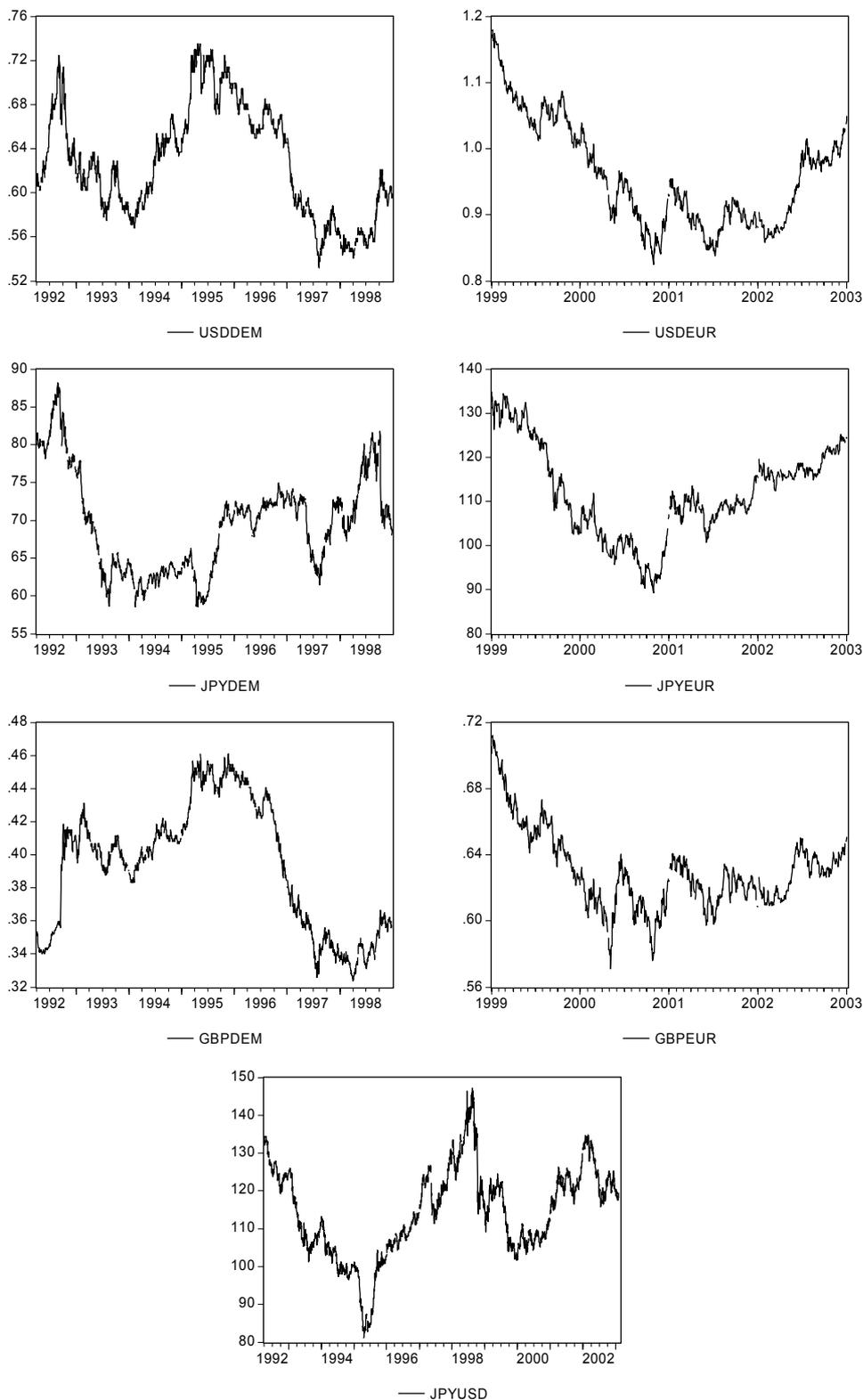


Figure 2: Realized Volatility, 1 and 3 Month Annualized

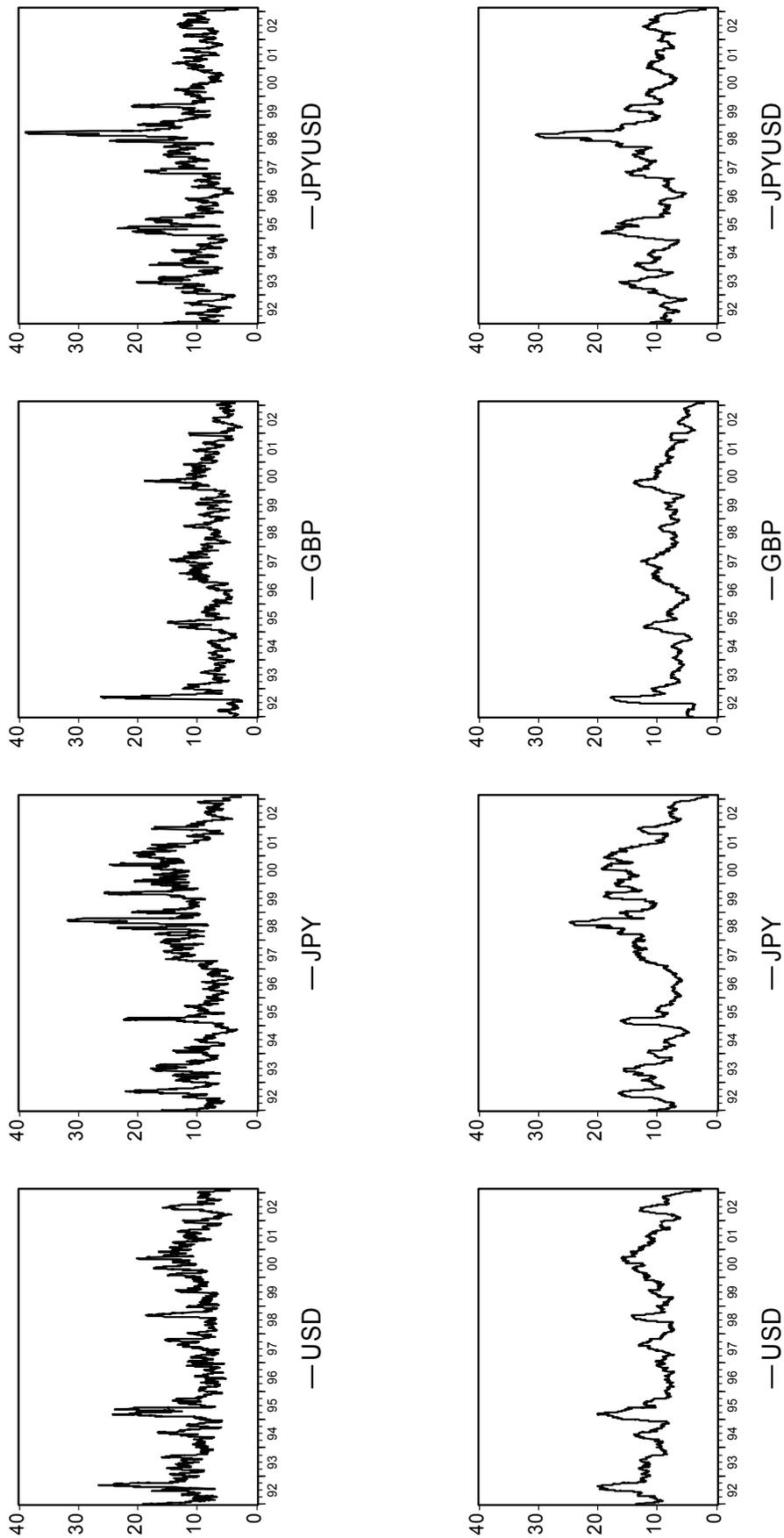


Figure 3: Implied Volatility from Options, 1 and 3 Month Annualized

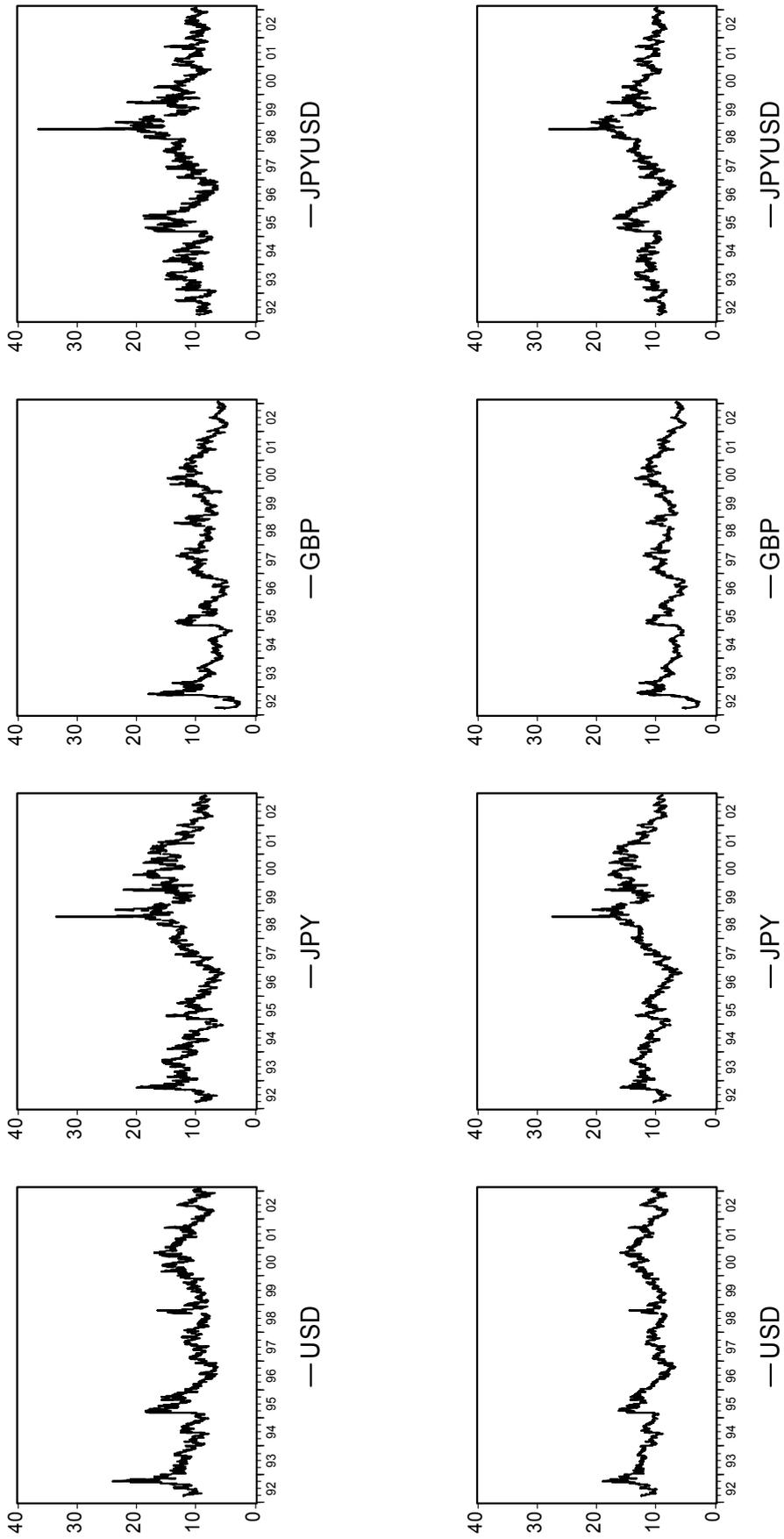


Figure 4: RiskMetrics Volatility, Annualized

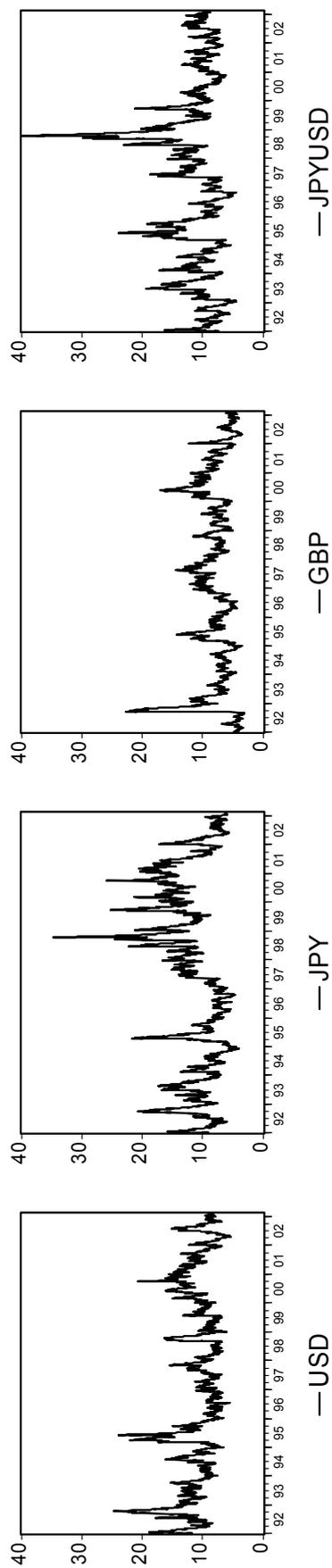


Figure 5: GARCH Volatility, 1 and 3 Month Annualized

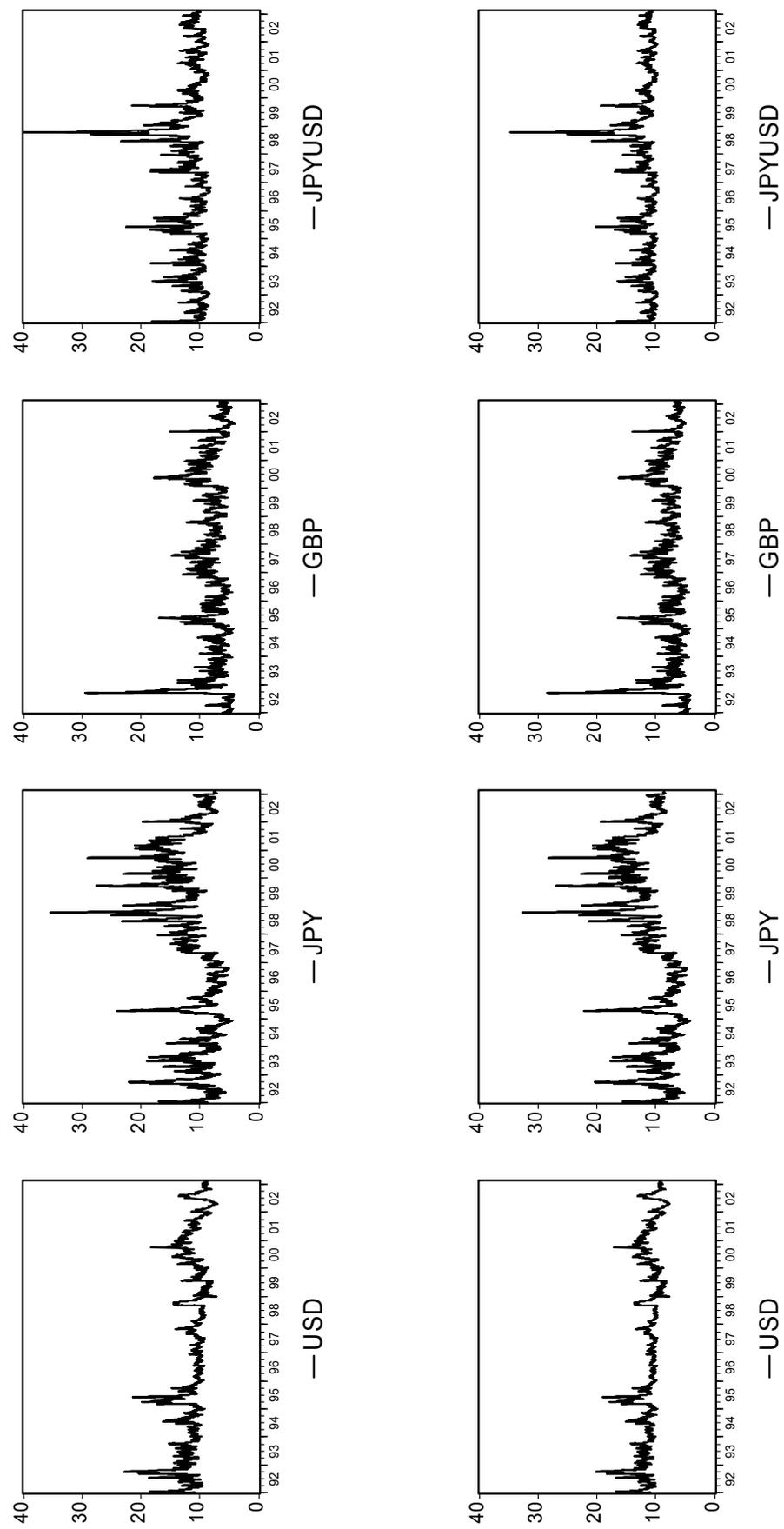


Figure 6: Interval Forecasts, Pre and Post Euro Introduction

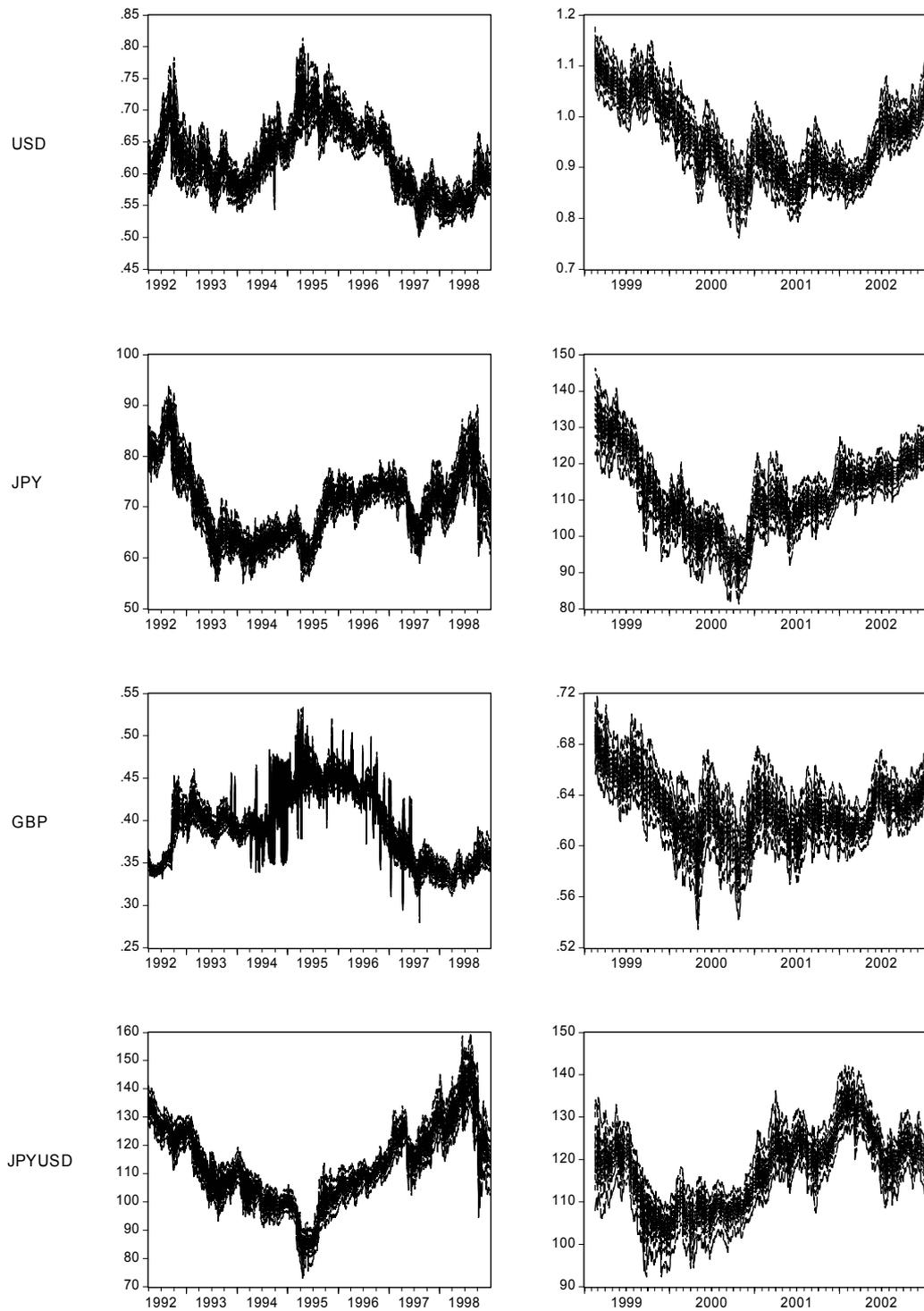


Figure 7: Histogram of Probability Transforms with 90% Confidence Band

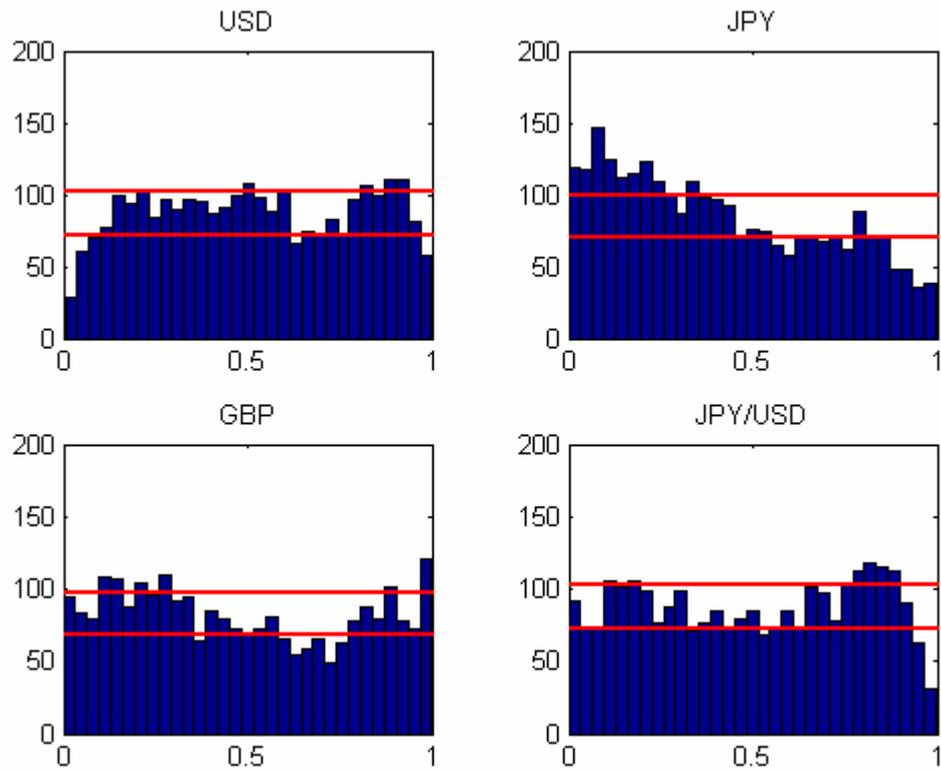


Figure 8: Histogram of Normal Transforms with Normal Distribution Imposed

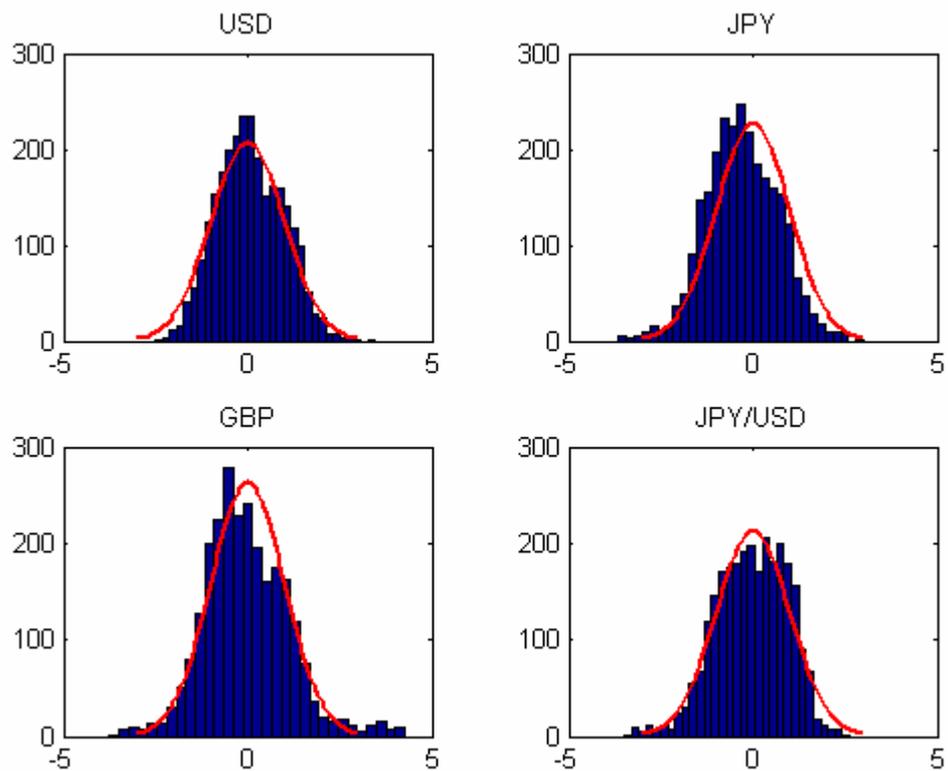


Figure 9: QQ Plots of Normal Transform Variables

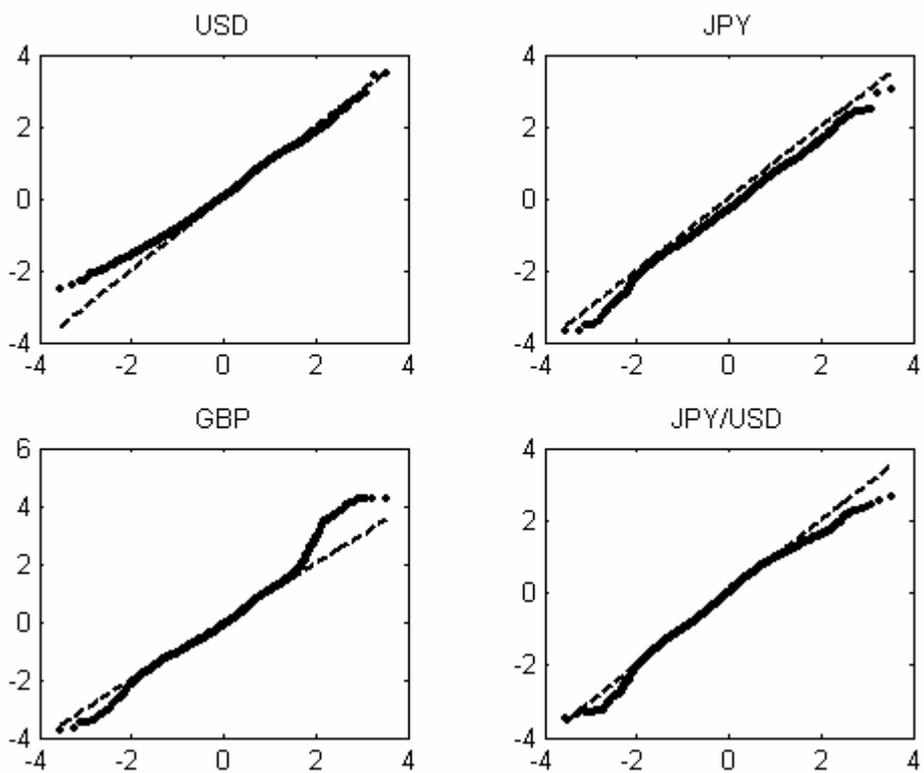


Table 1: 1-Month Volatility Predictability Regressions. Full Sample

USD						JPY					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
2.031 (0.984)	0.785 (0.096)				0.307	0.773 (1.019)	0.897 (0.094)				0.370
5.787 (0.729)		0.455 (0.073)			0.207	4.894 (0.841)		0.563 (0.078)			0.315
4.872 (0.873)			0.536 (0.086)		0.228	4.071 (0.888)			0.627 (0.082)		0.330
1.846 (1.320)				0.789 (0.123)	0.223	3.965 (0.863)				0.645 (0.079)	0.322
2.104 (0.970)	0.735 (0.120)	0.045 (0.081)			0.307	1.306 (0.976)	0.670 (0.143)	0.187 (0.113)			0.381
2.065 (0.964)	0.747 (0.133)		0.036 (0.111)		0.307	1.226 (0.949)	0.668 (0.146)		0.193 (0.129)		0.378
1.458 (1.247)	0.683 (0.121)			0.152 (0.157)	0.310	1.092 (0.979)	0.669 (0.141)			0.207 (0.120)	0.380
0.845 (1.617)	0.734 (0.132)	0.006 (0.145)	-0.137 (0.209)	0.283 (0.268)	0.311	1.244 (0.953)	0.669 (0.145)	0.168 (0.170)	-0.064 (0.176)	0.090 (0.166)	0.381
GBP						JPY/USD					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
1.654 (0.589)	0.749 (0.072)				0.342	0.838 (1.566)	0.876 (0.151)				0.324
4.152 (0.631)		0.465 (0.071)			0.217	5.028 (1.231)		0.537 (0.123)			0.286
3.735 (0.757)			0.513 (0.087)		0.218	4.262 (1.315)			0.599 (0.130)		0.302
3.219 (0.621)				0.582 (0.068)	0.235	1.206 (1.958)				0.851 (0.181)	0.287
1.639 (0.563)	0.769 (0.127)	-0.018 (0.118)			0.342	1.556 (1.240)	0.593 (0.180)	0.231 (0.180)			0.343
1.627 (0.581)	0.847 (0.156)		-0.098 (0.157)		0.344	1.521 (1.255)	0.558 (0.179)		0.268 (0.192)		0.342
1.552 (0.606)	0.661 (0.095)			0.104 (0.098)	0.345	-0.124 (1.936)	0.586 (0.163)			0.376 (0.271)	0.345
1.259 (0.544)	0.816 (0.145)	0.011 (0.117)	-0.347 (0.163)	0.319 (0.140)	0.359	0.643 (2.032)	0.541 (0.181)	0.089 (0.220)	0.043 (0.167)	0.227 (0.289)	0.346

Table 2: 3-Month Volatility Predictability Regressions. Full Sample

USD						JPY					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
3.308 (1.341)	0.674 (0.123)				0.210	0.808 (1.829)	0.911 (0.153)				0.349
6.445 (1.094)		0.398 (0.095)			0.150	4.653 (1.283)		0.589 (0.106)			0.333
6.399 (0.893)			0.405 (0.079)		0.189	5.206 (1.103)			0.548 (0.086)		0.332
2.145 (1.603)				0.780 (0.145)	0.199	5.536 (1.032)				0.543 (0.079)	0.288
3.361 (1.353)	0.645 (0.220)	0.024 (0.154)			0.210	1.770 (1.758)	0.578 (0.224)	0.253 (0.153)			0.365
3.860 (1.320)	0.457 (0.183)		0.172 (0.120)		0.222	1.954 (1.788)	0.565 (0.220)		0.253 (0.119)		0.371
1.538 (1.551)	0.422 (0.164)			0.412 (0.204)	0.237	1.413 (1.905)	0.692 (0.234)			0.180 (0.119)	0.361
1.128 (2.245)	0.513 (0.218)	-0.120 (0.151)	0.017 (0.190)	0.459 (0.333)	0.239	2.107 (1.765)	0.501 (0.251)	0.110 (0.158)	0.198 (0.236)	-0.003 (0.226)	0.372
GBP						JPY/USD					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
3.811 (1.743)	0.510 (0.195)				0.158	1.526 (2.667)	0.821 (0.254)				0.269
5.247 (1.289)		0.337 (0.139)			0.112	5.598 (1.396)		0.493 (0.141)			0.235
5.279 (1.172)			0.335 (0.127)		0.134	5.750 (0.962)			0.484 (0.099)		0.262
4.980 (1.152)				0.384 (0.129)	0.125	0.827 (1.656)				0.879 (0.149)	0.229
3.818 (1.735)	0.461 (0.204)	0.049 (0.123)			0.159	2.207 (2.568)	0.572 (0.278)	0.199 (0.119)			0.283
3.945 (1.745)	0.375 (0.215)		0.121 (0.077)		0.164	2.654 (2.452)	0.476 (0.269)		0.262 (0.085)		0.299
3.657 (1.732)	0.374 (0.218)			0.162 (0.057)	0.170	-0.488 (2.213)	0.563 (0.259)			0.429 (0.131)	0.298
3.649 (1.736)	0.375 (0.212)	0.002 (0.170)	-0.005 (0.113)	0.166 (0.065)	0.169	1.055 (2.622)	0.473 (0.278)	0.032 (0.130)	0.125 (0.122)	0.239 (0.159)	0.301

Table 3: 1-Month Volatility Predictability Regressions. High Frequency. Post 1999

USD						JPY					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
2.763 (0.721)	0.668 (0.063)				0.525	1.487 (0.903)	0.888 (0.067)				0.541
3.628 (0.885)		0.643 (0.085)			0.411	2.744 (0.997)		0.779 (0.080)			0.582
4.948 (0.844)			0.535 (0.080)		0.326	3.460 (1.193)			0.797 (0.107)		0.518
2.821 (1.166)				0.746 (0.112)	0.329	2.357 (1.652)				0.868 (0.140)	0.467
2.757 (0.744)	0.664 (0.116)	0.005 (0.123)			0.524	1.693 (0.849)	0.340 (0.152)	0.524 (0.149)			0.603
2.649 (0.685)	0.619 (0.091)		0.067 (0.070)		0.527	1.478 (0.884)	0.528 (0.160)		0.392 (0.174)		0.579
2.282 (0.738)	0.608 (0.089)			0.116 (0.095)	0.528	0.538 (1.009)	0.618 (0.137)			0.365 (0.180)	0.575
1.881 (0.841)	0.639 (0.122)	-0.035 (0.126)	-0.110 (0.096)	0.268 (0.138)	0.528	1.123 (0.941)	0.229 (0.159)	0.444 (0.144)	0.046 (0.195)	0.206 (0.197)	0.616
GBP						JPY/USD					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
1.971 (0.586)	0.816 (0.073)				0.648	3.850 (0.995)	0.529 (0.094)				0.330
1.701 (0.785)		0.803 (0.094)			0.641	4.502 (1.054)		0.532 (0.116)			0.285
3.651 (0.796)			0.657 (0.098)		0.394	5.156 (1.066)			0.489 (0.125)		0.238
3.480 (0.807)				0.667 (0.096)	0.393	2.744 (1.796)				0.679 (0.183)	0.231
1.593 (0.659)	0.442 (0.142)	0.396 (0.171)			0.669	3.605 (1.039)	0.383 (0.128)	0.190 (0.132)			0.341
2.093 (0.613)	0.902 (0.131)		-0.108 (0.121)		0.651	3.403 (1.055)	0.411 (0.102)		0.188 (0.112)		0.349
1.933 (0.630)	0.801 (0.093)			0.021 (0.087)	0.647	2.242 (1.481)	0.411 (0.089)			0.284 (0.155)	0.354
1.420 (0.645)	0.526 (0.127)	0.537 (0.193)	-0.631 (0.194)	0.398 (0.119)	0.699	2.215 (1.783)	0.367 (0.124)	0.085 (0.148)	-0.036 (0.175)	0.285 (0.255)	0.354

Table 3a: 1-Month Volatility Predictability Regressions. Daily. Post 1999

USD						JPY					
		Slopes					Slopes				
Intercept	IV	HV	RM	GH	Adj R ²	Intercept	IV	HV	RM	GH	Adj R ²
0.969 (1.385)	0.870 (0.124)				0.385	-1.292 (1.481)	1.078 (0.121)				0.490
5.566 (1.035)		0.477 (0.090)			0.225	4.538 (1.280)		0.627 (0.099)			0.374
4.715 (1.171)			0.553 (0.099)		0.240	3.571 (1.331)			0.695 (0.099)		0.386
2.710 (1.542)				0.744 (0.134)	0.234	3.151 (1.550)				0.713 (0.110)	0.341
0.979 (1.398)	0.861 (0.172)	0.008 (0.099)			0.385	-0.879 (1.505)	0.913 (0.185)	0.134 (0.106)			0.495
0.936 (1.397)	0.921 (0.205)		-0.050 (0.137)		0.385	-1.071 (1.540)	0.970 (0.233)		0.090 (0.151)		0.491
1.287 (1.365)	0.981 (0.226)			-0.145 (0.204)	0.387	-1.280 (1.488)	1.048 (0.213)			0.029 (0.136)	0.490
3.134 (1.435)	1.008 (0.243)	0.286 (0.239)	0.146 (0.137)	-0.780 (0.464)	0.397	-0.361 (1.417)	1.004 (0.237)	0.378 (0.139)	-0.042 (0.257)	-0.323 (0.156)	0.502
GBP						JPY/USD					
		Slopes					Slopes				
Intercept	IV	HV	RM	GH	Adj R ²	Intercept	IV	HV	RM	GH	Adj R ²
0.224 (0.992)	0.879 (0.122)				0.486	5.051 (1.712)	0.429 (0.161)				0.127
3.521 (0.767)		0.533 (0.103)			0.281	6.846 (1.051)		0.298 (0.110)			0.086
2.790 (0.841)			0.620 (0.108)		0.310	6.673 (1.188)			0.312 (0.121)		0.071
2.647 (0.911)				0.630 (0.113)	0.290	4.750 (1.695)				0.467 (0.160)	0.087
0.118 (1.023)	0.984 (0.177)	-0.101 (0.103)			0.489	4.950 (1.694)	0.343 (0.204)	0.106 (0.127)			0.132
0.170 (1.012)	1.001 (0.209)		-0.125 (0.145)		0.489	5.012 (1.664)	0.411 (0.231)		0.024 (0.164)		0.126
0.254 (1.011)	0.956 (0.177)			-0.086 (0.118)	0.488	4.530 (1.722)	0.363 (0.222)			0.116 (0.204)	0.128
0.076 (1.040)	0.996 (0.207)	-0.081 (0.168)	-0.093 (0.232)	0.064 (0.179)	0.489	4.966 (1.708)	0.397 (0.228)	0.285 (0.159)	-0.317 (0.215)	0.073 (0.254)	0.139

Table 4: 3-Month Volatility Predictability Regressions. High Frequency. Post 1999

USD						JPY					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
2.986 (1.275)	0.641 (0.103)				0.442	-0.240 (1.714)	1.019 (0.114)				0.571
3.617 (1.578)		0.640 (0.145)			0.370	1.002 (1.205)		0.896 (0.096)			0.674
6.166 (1.047)			0.412 (0.093)		0.246	4.003 (1.650)			0.747 (0.135)		0.499
3.372 (1.742)				0.699 (0.165)	0.247	1.216 (2.722)				0.937 (0.208)	0.415
2.622 (1.412)	0.493 (0.171)	0.198 (0.206)			0.453	0.133 (1.347)	0.247 (0.254)	0.722 (0.220)			0.681
2.985 (1.271)	0.636 (0.171)		0.006 (0.135)		0.442	0.238 (1.801)	0.723 (0.253)		0.281 (0.204)		0.593
2.830 (1.502)	0.623 (0.163)			0.037 (0.217)	0.442	-1.225 (1.650)	0.828 (0.200)			0.278 (0.217)	0.587
1.784 (1.853)	0.516 (0.195)	0.247 (0.208)	-0.179 (0.157)	0.186 (0.220)	0.456	-1.472 (1.417)	0.154 (0.296)	0.733 (0.209)	-0.167 (0.166)	0.374 (0.180)	0.691
GBP						JPY/USD					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
1.707 (0.794)	0.839 (0.101)				0.624	4.664 (1.055)	0.441 (0.097)				0.232
1.984 (1.107)		0.762 (0.128)			0.549	5.601 (1.202)		0.407 (0.123)			0.170
4.806 (1.081)			0.510 (0.109)		0.270	5.974 (1.017)			0.396 (0.116)		0.203
4.278 (1.246)				0.569 (0.129)	0.249	1.517 (2.118)				0.757 (0.201)	0.193
1.491 (0.862)	0.662 (0.145)	0.191 (0.136)			0.630	4.439 (1.180)	0.367 (0.107)	0.107 (0.123)			0.236
1.821 (0.733)	1.184 (0.233)		-0.386 (0.183)		0.673	4.210 (1.056)	0.300 (0.118)		0.221 (0.143)		0.270
2.238 (0.753)	1.019 (0.152)			-0.258 (0.126)	0.645	1.496 (2.069)	0.313 (0.108)			0.430 (0.239)	0.274
0.269 (0.983)	0.839 (0.191)	0.579 (0.176)	-1.010 (0.331)	0.525 (0.202)	0.730	1.709 (1.692)	0.264 (0.115)	0.069 (0.115)	0.028 (0.164)	0.373 (0.184)	0.275

Table 4a: 3-Month Volatility Predictability Regressions. Daily. Post 1999

USD						JPY					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
0.791 (2.116)	0.881 (0.182)				0.390	-3.104 (2.340)	1.224 (0.170)				0.545
4.781 (2.385)		0.548 (0.213)			0.259	3.079 (2.053)		0.726 (0.134)			0.420
5.718 (1.639)			0.464 (0.144)		0.234	4.114 (2.048)			0.656 (0.133)		0.407
2.660 (2.457)				0.762 (0.223)	0.238	2.799 (2.820)				0.722 (0.179)	0.333
0.752 (1.855)	0.911 (0.292)	-0.027 (0.336)			0.390	-2.869 (2.322)	1.133 (0.285)	0.071 (0.197)			0.545
0.542 (1.874)	0.985 (0.214)		-0.086 (0.195)		0.392	-3.005 (2.406)	1.196 (0.270)		0.020 (0.149)		0.544
1.123 (2.490)	1.002 (0.217)			-0.160 (0.314)	0.393	-3.114 (2.343)	1.278 (0.240)			-0.050 (0.137)	0.545
1.234 (1.995)	0.979 (0.308)	0.056 (0.347)	-0.011 (0.152)	-0.191 (0.291)	0.392	-2.147 (2.357)	1.169 (0.317)	0.035 (0.227)	0.181 (0.159)	-0.224 (0.087)	0.547
GBP						JPY/USD					
Intercept	IV	Slopes			Adj R ²	Intercept	IV	Slopes			Adj R ²
		HV	RM	GH				HV	RM	GH	
-0.449 (1.059)	0.959 (0.147)				0.611	7.144 (1.654)	0.235 (0.143)				0.043
2.411 (0.959)		0.669 (0.117)			0.394	9.095 (1.178)		0.069 (0.097)			0.003
3.058 (0.818)			0.595 (0.105)		0.381	8.471 (1.065)			0.133 (0.095)		0.018
2.225 (1.109)				0.697 (0.140)	0.323	6.677 (1.896)				0.277 (0.159)	0.022
-0.461 (1.074)	1.012 (0.298)	-0.055 (0.215)			0.611	7.438 (1.607)	0.295 (0.202)	-0.096 (0.162)			0.047
-0.620 (1.165)	1.094 (0.257)		-0.125 (0.155)		0.615	7.103 (1.566)	0.221 (0.219)		0.020 (0.168)		0.042
-0.300 (1.062)	1.064 (0.218)			-0.133 (0.134)	0.615	6.535 (1.989)	0.205 (0.210)			0.085 (0.281)	0.044
-0.548 (0.991)	1.083 (0.311)	0.033 (0.252)	-0.113 (0.171)	-0.043 (0.108)	0.615	7.302 (1.358)	0.259 (0.226)	-0.199 (0.140)	0.129 (0.213)	0.027 (0.212)	0.054

Table 5: Interval Regressions

	USD		JPY		GBP		JPY/USD	
p = .90	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.046	0.905	-0.007	-0.164	0.074	1.799	0.120	2.873
Lag hit	-0.005	-0.208	-0.005	-0.224	0.031	1.207	-0.016	-0.722
1 month IV	-0.005	-1.359	0.002	0.625	-0.011	-2.886	-0.008	-2.380
Average Hit	0.887	-1.362	0.911	1.259	0.912	1.231	0.912	1.389
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald Test	3.9176	0.2705	2.0668	0.5587	14.9576	0.0019	11.2946	0.0102
p=.70	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.277	2.955	0.062	0.702	0.347	5.540	0.277	2.947
Lag hit	-0.077	-2.381	-0.015	-0.476	-0.021	-0.721	-0.007	-0.224
1 month IV	-0.022	-2.731	-0.002	-0.341	-0.034	-4.546	-0.021	-2.726
Average Hit	0.681	-0.932	0.724	1.227	0.755	2.689	0.727	1.382
Wald Test	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
	12.54	0.01	1.91	0.59	38.61	0.00	13.02	0.00
p=.50	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.313	2.674	0.123	1.134	0.496	6.107	0.292	2.808
Lag hit	-0.077	-2.055	-0.022	-0.590	0.011	0.316	-0.005	-0.126
1 month IV	-0.026	-2.497	-0.006	-0.773	-0.053	-5.897	-0.023	-2.613
Average Hit	0.494	-0.232	0.534	1.283	0.570	2.521	0.526	1.020
Wald Test	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
	11.33	0.01	2.50	0.48	42.64	0.00	8.77	0.03
p=.30	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.287	2.526	0.151	1.361	0.431	4.716	0.246	2.540
Lag hit	-0.090	-2.590	-0.027	-0.635	0.152	3.452	-0.031	-0.732
1 month IV	-0.027	-2.724	-0.011	-1.312	-0.052	-5.365	-0.022	-2.857
Average Hit	0.271	-1.196	0.306	0.234	0.370	2.293	0.284	-0.617
Wald Test	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
	22.20	0.00	1.96	0.58	45.28	0.00	9.00	0.03
p=.10	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.074	1.196	0.045	0.593	0.280	3.427	0.017	0.256
Lag hit	-0.075	-3.854	0.000	0.004	0.297	3.534	-0.030	-1.034
1 month IV	-0.009	-1.928	-0.004	-0.633	-0.032	-3.771	-0.004	-0.784
Average Hit	0.066	-2.628	0.097	-0.139	0.166	2.424	0.065	-2.411
Wald Test	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
	154.32	0.00	0.42	0.94	30.49	0.00	8.12	0.04

Table 6: Interval Regressions. Post 1999

	USD		JPY		GBP		JPY/USD	
p = .90	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	-0.035	-0.378	-0.167	-2.057	-0.023	-0.315	0.235	4.061
Lag hit	0.014	0.320	0.009	0.267	-0.003	-0.086	-0.031	-1.368
1 month IV	0.001	0.167	0.012	2.115	0.001	0.192	-0.017	-3.885
Average Hit	0.895	-0.364	0.894	-0.391	0.889	-0.653	0.910	0.781
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald Test	0.44	0.93	4.58	0.21	0.80	0.85	17.14	0.00
p=.70	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.252	1.207	-0.198	-1.151	0.125	0.994	0.566	3.729
Lag hit	-0.042	-0.749	-0.023	-0.501	-0.103	-2.275	-0.097	-2.087
1 month IV	-0.023	-1.274	0.016	1.337	-0.008	-0.531	-0.043	-3.462
Average Hit	0.673	-0.782	0.687	-0.404	0.689	-0.370	0.702	0.060
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald Test	2.63	0.45	2.42	0.49	6.12	0.11	14.57	0.00
p=.50	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.335	1.249	-0.153	-0.788	0.047	0.281	0.549	3.235
Lag hit	-0.050	-0.867	-0.032	-0.609	-0.094	-1.946	-0.070	-1.135
1 month IV	-0.029	-1.208	0.011	0.800	-0.009	-0.440	-0.042	-3.082
Average Hit	0.488	-0.280	0.474	-0.622	0.441	-1.610	0.521	0.520
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald Test	2.61	0.46	1.37	0.71	6.06	0.11	10.47	0.02
p=.30	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	0.167	0.614	-0.098	-0.557	-0.107	-0.649	0.479	3.036
Lag hit	-0.005	-0.085	-0.014	-0.233	-0.079	-2.085	-0.086	-1.580
1 month IV	-0.017	-0.696	0.004	0.336	0.002	0.102	-0.043	-3.598
Average Hit	0.278	-0.539	0.245	-1.279	0.201	-3.287	0.260	-1.020
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald Test	0.99	0.80	1.55	0.67	18.82	0.00	20.24	0.00
p=.10	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Constant	-0.083	-0.788	-0.078	-0.994	-0.088	-2.420	0.020	0.327
Lag hit	-0.051	-3.722	0.039	0.638	-0.019	-2.894	-0.049	-2.573
1 month IV	0.003	0.338	0.002	0.309	0.001	0.189	-0.008	-1.573
Average Hit	0.046	-4.436	0.048	-2.577	0.019	-11.347	0.032	-6.065
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald Test	2807.35	0.00	10.64	0.01	11270.03	0.00	1637.73	0.00

Table 7: GMM Test for Unconditional Normality of Z Score

	USD		JPY		GBP		JPY/USD	
	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Mean	0.072	1.018	-0.297	-4.031	-0.024	-0.278	-0.040	-0.525
Var	-0.201	-3.284	-0.070	-0.809	0.343	2.244	-0.073	-0.838
Skew	0.163	0.732	-0.033	-0.120	0.490	1.511	-0.359	-1.243
Kurt	-0.299	-0.727	0.180	0.297	1.153	1.247	0.031	0.043
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald-test	50.56	0.00	64.02	0.00	29.61	0.00	7.49	0.11

Table 8: GMM Test for Unconditional Normality of Z Score. Post 1999

	USD		JPY		GBP		JPY/USD	
	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Mean	-0.017	-0.147	-0.017	-0.159	-0.047	-0.508	-0.032	-0.294
Var	-0.230	-2.723	-0.217	-1.797	-0.392	-5.851	-0.256	-3.218
Skew	0.244	0.816	0.370	0.844	0.237	0.782	0.089	0.302
Kurt	-0.693	-1.839	-0.136	-0.140	-0.685	-1.450	-0.772	-1.888
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald-test	32.09	0.000	26.15	0.000	308.11	0.000	38.12	0.000

Table 9: GMM Test for Conditional Normality of Z Score

	USD		JPY		GBP		JPY/USD	
	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Const	0.621	1.962	-0.346	-1.271	0.780	2.762	-0.088	-0.307
Lag LHS	0.128	2.295	0.145	2.573	0.304	4.328	0.120	1.911
1MIV(-21)	-0.050	-1.861	0.010	0.448	-0.095	-3.115	0.006	0.247
Const	0.030	0.197	0.128	0.726	0.854	3.635	0.160	0.929
Lag LHS	-0.122	-3.540	-0.023	-0.463	0.332	3.150	-0.011	-0.266
1MIV(-21) ²	-0.002	-2.046	-0.001	-1.154	-0.009	-4.003	-0.002	-1.751
Const	0.605	1.563	-0.239	-0.680	0.860	2.083	-0.365	-0.956
Lag LHS	0.021	0.911	0.093	2.185	0.328	2.665	0.068	2.239
1MIV(-21) ³	0.000	-1.674	0.000	1.069	-0.001	-2.258	0.000	0.413
Const	0.165	0.279	0.334	0.610	1.675	1.861	0.170	0.214
Lag LHS	-0.047	-2.084	-0.001	-0.048	0.312	2.152	-0.014	-0.833
1MIV(-21) ⁴	0.000	-1.815	0.000	-0.541	0.000	-2.710	0.000	-1.208
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald-test	106.61	0.000	157.65	0.000	118.43	0.000	50.72	0.000

Table 10: GMM Test for Conditional Normality of Z Score. Post 1999

	USD		JPY		GBP		JPY/USD	
	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>	<u>Estimate</u>	<u>t-stat</u>
Const	1.035	1.608	0.562	1.349	0.440	1.077	-0.016	-0.034
Lag LHS	0.191	1.874	0.089	0.820	0.056	0.663	0.076	0.749
1MIV(-21)	-0.093	-1.580	-0.044	-1.331	-0.057	-1.196	-0.001	-0.038
Const	-0.172	-0.505	-0.330	-1.370	-0.422	-2.056	0.187	1.118
Lag LHS	-0.025	-0.444	0.024	0.283	-0.075	-1.240	-0.115	-1.925
1MIV(-21) ²	0.000	-0.177	0.001	0.519	0.000	-0.089	-0.003	-3.589
Const	0.856	1.110	0.307	0.563	0.507	0.938	0.016	0.033
Lag LHS	0.111	1.633	0.138	1.487	0.052	0.655	0.076	1.116
1MIV(-21) ³	0.000	-0.766	0.000	0.058	0.000	-0.640	0.000	0.242
Const	-1.172	-1.305	-0.636	-0.832	-0.869	-1.142	-0.145	-0.263
Lag LHS	-0.032	-0.820	0.040	0.692	-0.031	-0.631	-0.065	-1.914
1MIV(-21) ⁴	0.000	0.612	0.000	0.591	0.000	0.156	0.000	-2.871
	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>	<u>Stats</u>	<u>p-val</u>
Wald-test	81.38	0.00	169.79	0.00	439.99	0.00	77.57	0.00

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