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Volatility Transmission in the Exchange Rate of the Indian Rupee

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Abstract

The paper analyzes volatility spillovers from the exchange rates of the Brazilian Real, the Russian Ruble, the South Korean Won, the Singapore Dollar, the Japanese Yen, the Swiss Franc, the British Pound Sterling and the Euro to the exchange rate of the Indian Rupee during 2005-11. The study employs a two-step multivariate GARCH framework to examine the dynamics of exchange rate volatility and its spillovers which is also corroborated by examining simple pair-wise Granger causality tests. All the currencies included in the study exhibit presence of conditional autocorrelation and persistence of volatility in daily exchange rates. The findings support the view that volatilities observed in the exchange rate of the leading currencies, inter alia, cause volatility in the daily exchange rate of the Indian Rupee.

Key words: exchange rate, volatility transmission, GARCH

JEL classification: F31, C32, F41

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Introduction

The recent fall in the exchange rate of the leading currencies surfaced renewed concerns among policy makers as well as investors in examining the nature and causes of such sharp decline. All emerging economy currencies depreciated sharply against the US Dollar in the second-half of 2011 with the exchange rate of the Indian Rupee (INR) said to be the worst performing currency among them. Emerging market economies (EMEs) with a surplus or a small deficit in the current account were less hit than countries that have a sizeable deficit like India. Although the sharp fall and volatility in the exchange rate of the Indian rupee could be largely attributed to macroeconomic factors, *inter alia*, current account deficit and capital outflows, wherein spillover effects emanating from other volatile markets due to differences in timing of trading activity, bid-ask spreads and risk perceptions cannot be ruled out. Furthermore, the recent sharp fall in the exchange rate of the Indian rupee could also be attributed to the growing integration among the financial markets world over in which the confidence channel seems to have also played a significant role against the backdrop of the Eurozone sovereign debt crisis and the consequent external economic environment.

In the past decades, there has been an unprecedented increase in cross border transactions between countries in terms of goods and financial flows leading to growing integration of emerging markets with the developed one. This integration has been further fuelled by search for higher returns, risk diversification, cost effective and more efficient factors of production and expectation of global dominance in the world wide market place. An important result of these capital flows was its impact on linkages of global asset returns and spillover of volatility from one capital market to another. As a result, a financial crisis originating in a particular country/region, has extended geographically which included large and unexpected movements in the prices of various financial instruments, including foreign exchange rates (Dooley and Hutchinson, 2009; Melvin and Taylor, 2009; and Muller and Verschoor, 2009).

Looking into the spillover effect of volatility from one market to another, a clear distinction is warranted between the concepts of interdependency and contagion (Soriano, 2006). Interdependency is a much wider concept which includes all types of interrelations including both in mean and in variance that may exist between two assets or markets, whereas it appears that existing literature has not arrived at an agreement for a common definition of the concept of contagion. In this context, empirical research on relations between financial markets could be traced back to the concept of autoregressive conditional heteroscedasticity (ARCH) advocated by Engle (1982) which has been further extended by the generalized autoregressive conditional heteroscedasticity (GARCH) model proposed by Bollerslev (1986). Furthermore, Engle *et al*. (1990) advocated the concept of *heat waves* and *meteor showers* which is largely applicable to study intra-day volatility. The hypothesis of *heat waves* is consistent with the idea that most of the volatility sources are country/region specific, *e.g*., volatility in Mumbai today is correlated with volatility in Mumbai tomorrow. Under this hypothesis, market-making dealers typically adjust their positions quickly in response to new information which is expected to be contained within the region. On the contrary, the *meteor shower* hypothesis is consistent with the idea of shock transmission between different markets, countries or regions. Under this hypothesis, volatility is autocorrelated across regions, *i.e*., public information received at one point of time is followed with a lag by a stochastic response.

Although there are quite a number of studies in examining volatility transmission from global stock markets to the Indian stock markets, there is hardly any study relating to the Indian foreign exchange market. Therefore, the contribution of this paper to the existing literature is a thorough study of volatility transmission from major exchange rates to the INR using high frequency data. Motivated by the impact of the recent crisis, this study analyzes the dynamics of volatility transmission from foreign exchange markets in the EMEs and advanced economies (AEs) to the Indian foreign exchange market. In particular, we analyze volatility spillovers from the Brazilian Real (BRL), the Russian Ruble (RUB), the South Korean Won (KRW), the Singapore Dollar (SGD), the Japanese Yen (JPY), the Swiss Franc (CHF), the British Pound Sterling (GBP) and the Euro (EUR) to the Indian Rupee (INR) during the period 2005–2011. The study employs a two-step multivariate GARCH framework first developed by Hamao, *et al.* (1990) to study the dynamics of stock market volatility and its spillovers. The findings are also corroborated by examining cross-correlations and running simple pair-wise Granger (1969) causality test. The empirical findings suggest that exchange rate of the Indian Rupee could not be insulated from volatilities in the exchange rate of leading currencies in the AEs as well as EMEs.

The structure of the paper is the following. Section II provides a brief review of the literature on volatility transmission focusing primarily on the contributions that are most relevant for this study. In Section III, a brief review on India's exchange rate policy and some stylized facts on the recent developments in the exchange rate of the major currencies are reported. The methodology is presented in Section IV. The empirical findings and its implications are discussed in Section V. The concluding section summarizes the findings of the paper and suggests some further extensions of the study.

II. Related Literature

Ever since the advent of the ARCH model by Engle (1982), research on the transmission mechanism of volatility between various segments of the financial market has been fast advancing. The application of ARCH and its generalized form, *i.e.*, GARCH has advanced rapidly in examining volatility transmission among stock markets. Studies on volatility transmission based on low-frequency foreign exchange data are, however, relatively sparse. The initial application of GARCH model to the foreign exchange market could be traced back to the works of Diebold and Nerlove (1989). They employed a vector autoregressive (VAR) model as a basis for the variance decomposition of forecast error variances in order to measure the magnitude of return and volatility spillovers in the foreign exchange market. Bollerslev (1990) used a model with time-varying conditional variances and covariances, but constant conditional correlations, to model a set of five nominal European-US Dollar exchange rates in the period before and after the inception of the European Monetary System (EMS). Engle, *et al.* (1990) examined the *heat waves* and *meteor showers* hypothesis with the help of GARCH model using intra-daily data. Their empirical evidence was generally against the *heat wave* hypothesis. However, in terms of country-specific news, they found that Tokyo news had the largest impact on the volatility spillovers of the JPY/USD exchange rate.

Thereafter, Kearney and Patton (2000) employed a series of multivariate GARCH models to analyze the volatility transmission between the members of the

EMS prior to their complete monetary unification. They provided many interesting findings on the exchange rate volatility transmissions within the EMS including the effect of time-aggregation on volatility transmission. In fact, less volatile weekly data was found to exhibit a significantly smaller tendency to transmit volatility compared to the more volatile daily data. This finding was consistent with the fact that markets have a greater propensity to transmit volatility in active as opposed to tranquil periods, as shown by Andersen and Bollerslev (1998).

Hong (2001) pursued a different approach by studying the existence of Granger causalities between two weekly nominal US Dollar exchange rates with respect to (the former) the Deutsche Mark (DEM) and the Japanese Yen (JPY). His findings suggested only simultaneous interaction between the two exchange rates when it comes to causality in the mean and both simultaneous and one-way (DEM-JPY) interactions regarding the causality in the variance. Melvin and Melvin (2003) provided evidence of statistically significant intra- and inter-regional volatility spillovers in the DEM/USD and JPY/USD foreign exchange markets, given the theoretical settings of *heat waves* and *meteor showers* effects offered by Engle, *et al.* (1990). Chowdhury and Sarno (2004) also applied multivariate stochastic volatility models to analyze volatility spillovers across exchange rates. Bubak, *et al*. (2010) studied dynamics of volatility transmission between Central European currencies and euro/dollar foreign exchange using model-free estimates of daily exchange rate volatility based on intra-day data. They formulated a flexible yet parsimonious parametric model in which the daily realized volatility of a given exchange rate depends both on its own lags as well as on the lagged realized volatilities of the other exchange rates. They found evidence of statistically significant intra-regional volatility spillovers among the Central European foreign exchange markets. Lee (2010) employed multivariate GARCH model to test for cross-country mean and volatility transmission among ten emerging foreign exchange markets in Asia and Latin America while allowing for possible risks, leverage and persistence effects. The findings suggested presence of both regional spillovers and the transmission of shocks from external stock and foreign exchange markets. The spillovers from external markets were larger to Asian than Latin American currency markets.

In the Indian context, there is hardly any study examining the spillover effect of foreign exchange market volatility. There are, however, a few studies employing

GARCH model to estimate volatility of the exchange rate of the Indian rupee, *per se*, while analyzing the effectiveness of central bank intervention. For example, Goyal and Arora (2010) examined the impact of conventional monetary policy measures such as interest rates, intervention and other quantitative measures, compared to central bank communication on the exchange rate level and volatility. They found that quantitative intervention was the most effective among all the central bank instruments. Their findings were in conformity with most of the earlier studies that found Reserve Bank intervention decreases volatility (Pattanaik and Sahoo, 2003; Edison *et al*., 2007; and Goyal *et al*., 2009).

III. Stylized Facts

Since independence, India's exchange rate policy has evolved over time in tandem with global developments and gradual opening up of the economy as part of the broader strategy of macroeconomic reforms initiated in early 1990s. India's exchange rate policy has transited from a par value system to a basket-peg and further to a managed float exchange rate system. Since March 1993, India has been operating with a managed flexible regime, where the objective is not to achieve any explicit or implicit target for the exchange rate but to contain volatility by ensuring orderly market conditions. The regime could be interpreted as "more flexible" during normal market conditions with the accent shifting to "management" when the market turns disorderly. While in case of the former, intervention could be viewed as "passive", in case of the latter, intervention is "active". In other words, the objective behind passive intervention could be to "avoid a nominal appreciation" whereas in case of active intervention, the objective is to "avoid disruptive market corrections". Furthermore, during phases of active intervention, a combination of "leaning with the wind" and "leaning against the wind" may be applied, depending on the perceptions about the extent of accumulated misalignment at the beginning of any episode of exchange market pressure. The policy of "leaning with the wind" may be applied when the correction for the perceived misalignment is ensured by the market forces in an orderly manner. On the other hand, when the market correction turns disorderly – as reflected in heightened volatility – or when the market gets driven primarily by destabilizing speculation, pursuing a policy of "leaning against the wind" becomes inevitable (Pattanaik and Sahoo, 2003).

With the gradual removal of restrictions on many of capital account transactions, particularly in the past few years, the exchange rate regime in India has also been described as a "bounded float" (Gokarn, 2012). The Reserve Bank, however, does not target the level of exchange rate, nor it has a fixed band for nominal or real exchange rates to guide interventions, the capital account management framework helps in the bounded float. There are few controls on capital account such as imposition of limits on foreign direct investment on specific sectors and on portfolio investment in equities. However, there are controls on debt inflows, driven by considerations of external stability and they are altered relatively infrequently in response to changing macroeconomic conditions and not with a view to impacting the daily movement of the exchange rate. If volatility in the exchange rate of the Indian Rupee increases, appropriate tools, including those in the domain of capital account management are used. Within these overall boundaries, the exchange rate is determined by daily variations in demand and supply. Reserve Bank's policy approach does not involve strong intervention in the currency market to achieve a specific rate target. However, in excessively volatile market conditions, "smoothing" interventions are carried out that help to keep markets orderly and prevent large jumps that can induce further spirals. Therefore, the objective of exchange rate management is to find a balance between the short-term risk of the Indian Rupee spiraling downwards and the medium-term risk of a loss of confidence in meeting external obligations.

Before we move to examine the spillover effects of volatility in other currencies to the Indian Rupee, it is imperative to look into the movements in the major international currencies in the recent years. In 2007, while the currencies of AEs witnessed moderate appreciation against the US Dollar, those of EMEs experienced sharp appreciation (Table 1). The Euro traded within a relatively narrow range in the first half of 2007 and stayed range-bound until late July and then began a run of steady depreciation. The early period US subprime problems and aggressive Federal Reserve interest rate cuts were reflected in the US Dollar weakness against the Euro. The later period involved the flight-to-quality associated with the post-Lehman Brothers debacle and a strong sell-off of emerging markets, which benefited the US Dollar. In contrast, the Japanese Yen was appreciating against the US Dollar once the crisis began in August 2007. But after Bear Stearns sale and the appearance of more normal market conditions, the Yen underwent a period of depreciation that ended in September 2008. In the post-Lehman world, the Yen benefited from unwinding of carry trades where investors were short selling Yen futures, and also formed a view that the Yen was a safe-haven currency as Japanese banks did not suffer from US subprime exposure as did their competitors in Europe and the US. However, as the news on the macro economy in Japan became progressively worse beginning early 2009, the safe-haven notion disappeared. The UK pound sterling (GBP) had remained remarkably stable relative to the US Dollar through the early waves of the crisis. This trend changed in the summer of 2008 as the depth of the problems in British banks was revealed and the market began to price in the deterioration in UK economic conditions resulting from the magnitude of the unemployment and fiscal issues. Barring the JPY, major international currencies depreciated *vis-à-vis* the US Dollar in the second half of 2011.

Exchange rates of leading EMEs currencies such as the KRW, the RUB, the BRL and the INR witnessed sharp falls in 2008 in contrast to high appreciations in 2007 (Table 1 and Chart 1). While these EMEs appeared to be initially decoupled from the US financial crisis, they experienced large depreciations that greatly exceeded the initial appreciations of their currencies from early 2007 though mid-2008. Barring the BRL, other currencies remained broadly stable during 2009-10 and in the first half of 2011. In the second half of 2011, depreciation in the BRL was the highest followed by the INR, the RUB and the KRW. With the deepening of the Euro area crisis, EMEs were severely affected as investors repatriated over USD 25 billion from emerging market funds during August-September 2011, notably from equity funds (BIS, 2011). Emerging market equity prices fell sharply in September 2011, even more sharply than developed market equity prices, after the volatility of investor portfolios escalated. Conversion of emerging market assets into Euros put downward pressure on EMEs exchange rates, which fell sharply in September 2011. Several central banks in EMEs intervened in the currency markets to support their exchange rates.

The Indian Rupee which had remained broadly unchanged in the first half of 2011, depreciated by 15.8 per cent in the second half. The sharpest fall in the exchange rate of the Indian Rupee was during August-December 2011, reflecting capital flow moderation coupled with higher trade deficit. Against the backdrop of the prevailing external economic environment, the confidence channel seems to have also played a significant role in the sharp fall of the Indian Rupee. The Reserve Bank intervened to curb speculation in the market and encouraged capital flows of a more stable nature. It deregulated interest rates on NRI (non-resident Indian) rupee deposits, raised the limits on FII (foreign investor) exposure to equity and debt markets and tried to curb speculation. The foregoing analysis reveals that sharp fall in the exchange rate of the Indian Rupee in the later part of 2011 was in tandem with the fall in the exchange rates of major AEs and EMEs. Therefore, an inquiry into the volatility spillover from these currencies to the Indian Rupee would offer further insights. However, spillover effect should not be construed as the only factor in driving the recent volatility of the Indian Rupee. The exchange rate of the Indian Rupee is also driven by short-term factors, *viz*., volatile capital flows and news and long-term factors, *viz*., macroeconomic fundamentals, balance of payments position, stance of monetary and fiscal policies (Subbarao, 2012).

IV. Methodology

We use three broad approaches, *viz*., cross correlations among exchange rates, Granger causality and GARCH model to examine the spillover effect of volatility in the exchange rate of the foreign currency to the exchange rate of the Indian rupee. Although the first two approaches do not exactly verify the spillover effect, they give an idea beforehand about degree of correlation and the causal relationship, respectively. Since the advent of the concept of ARCH by Engle (1982), a host of studies applied and extended this methodology to capture the extent of changing volatility in a time series. In ARCH model, the conditional variance h is a linear function of past squared errors ε's derived from the mean equation, as well as possible exogenous variables.

$$R_t = \alpha + \varepsilon_t \quad \ldots(1)$$

where R_t is the variable of interest and ε_t is a white-noise disturbance term with constant variance.

$$h_t = a + c\varepsilon_{t-1}^2 + gX_t \quad \ldots(2)$$

where a>0 and c, g ≥0. The conditional variance equation in ARCH models does not include a stochastic component, but the models can include additional squared error terms from past periods.

To circumvent the difficulties in estimating ARCH models with large number of parameters, Bollerslev (1986) introduced GARCH model by allowing the conditional variance h to be a function not only of last period's error squared but also of its conditional variance. The GARCH(1,1) model defines the conditional variance of R at time t to be of the form:

$$h_t = a + bh_{t-1} + c\varepsilon_{t-1}^2 + gX_t \quad \ldots(3)$$

The above GARCH formulation can also be extended to include squared errors from the prior periods in the conditional variance equation. The stability property of the above GARCH process requires that the coefficients of the lagged errors and lagged conditional variances must sum to less than one.

In practice, the choice of conditional mean specification as given in equation (1) above is an important, yet largely ignored, issue in tests for volatility spillovers. Engle, *et al*. (1987) extended the GARCH model to allow the conditional mean to be a function of the conditional variance at time t, which is popularized as GARCH-M model. A typical GARCH(1,1)-M model takes the form

$$R_t = \alpha + \beta h_t + \varepsilon_t \quad \ldots(4)$$

where the conditional variance is defined in the same way as the GARCH(1,1) model. We estimate three conditional mean specifications, *viz*., simple conditional mean, including conditional variance in the mean equation and a first-order autoregressive process while examining the volatility pattern in the exchange rates.

We follow a two-step approach developed by Hamao *et al*. (1990) that applied the univariate GARCH methodology to analyze relations between international stock markets. First, different variants of GARCH models are estimated for each one of the markets individually to measure volatility. Second, the squared residuals (RESSQ) of the previous estimated models are used as regressors in the variance equation of the exchange rate of the Indian Rupee. By following this approach, one can determine if there exists a relation between the domestic market variance and the volatility surprise of the exchange rate of the leading currencies. For example, a

GARCH(1,1) model with AR(1) in the conditional mean specification has the following steps:

Step I

$$\Delta \ln EX_{i,t} = c_{i,0} + \eta_{i,0} \Delta \ln EX_{i,t-1} + \varepsilon_{i,t} \quad \ldots(5)$$

$$\sigma^2_{i,t} = \alpha_{i,0} + \beta_{i,0} \varepsilon^2_{i,t-1} + \gamma_{i,0} \sigma^2_{i,t-1} + \delta_{i,0} DUM_t \quad \ldots(6)$$

Step II

$$\Delta \ln INR_{i,t} = c_{i,1} + \eta_{i,1} \Delta \ln INR_{i,t-1} + \varepsilon_{i,1,t} \quad \ldots(7)$$

$$\sigma^2_{i,1,t} = \alpha_{i,1} + \beta_{i,1} \varepsilon^2_{i,1,t-1} + \gamma_{i,1} \sigma^2_{i,1,t-1} + \phi_i RESSQ_{i,t} + \delta_{i,1} DUM_t \quad \ldots(8)$$

where EX_i is exchange rate of currency i *vis-à-vis* the US dollar. DUM represents 0 for the pre-Lehman period, *i.e.*, prior to September 2008 and 1 for the post-Lehman period, *i.e.*, from September 2008 onwards.

V. Data and Empirical Findings

The study uses daily closing exchange rate of major currencies for the period from January 2005 to December 2011 sourced from Bloomberg. The exchange rate is defined as units of domestic currency per one unit of US dollar. Before we proceed for estimation of GARCH models, the descriptive statistics of all the exchange rates are analyzed separately for the pre-Lehman period, post-Lehman period and full sample period (Tables 2 to 4). However, there are no significant differences among the descriptive statistics of three sample periods. As per the various indicators shown in these three tables, we observe that daily exchange rates do not follow a normal distribution on the following grounds. First, the mean of all series are not statistically different from zero. Second, skewness moment is different from 0 and in most of the cases is negative. The negative values imply the leverage effect – the negative correlation between changes in the volatility and the changes in the market exchange rate. Third, Kurtosis moment registers high values in many cases. Fourth, Jarque-Bera (JB) statistics must show non-significance in order for the daily returns to follow the normal distribution. In our case, as the value of the probability from these tables show, the JB statistics is significant meaning that there are too many values near the mean and too many out in the extreme tails. This nature of non-normal distribution demonstrates volatility clustering meaning that large changes tend to be followed by large changes, but of random sign, whereas small changes tend to be followed by small changes.

The correlation coefficients (Tables 5 to 7) among the exchange rates are not very large but offer some useful insights. First, there are no large differences in the magnitude of correlation coefficients across the three sets of sample. Second, the correlation coefficients of INR with RUB, KRW and GBP are marginally higher in the post-Lehman period than those in the pre-Lehman period. As the correlation coefficients are not distinctly different in the full sample from those in the pre-Lehman and post-Lehman samples, the Granger causality test and GARCH models are estimated for the full sample only.

We perform the Granger causality test by running bivariate regressions for all possible pairs by taking first difference of each series as they are non-stationary at levels but stationary at first differences (Table 2). First, one-way causality running from CHF, EUR, GBP, RUB, KRW and SGD to INR imply that movement in the exchange rate of the rupee is caused by these currencies but not *vice-versa*. One-way causality running from the closing rates of Asian currencies, *viz*., KRW and SGD to the INR imply that today's closing level of INR, *inter alia*, is caused by past levels of these currencies reflecting time differences in trading among these markets. Similarly, past values of European currencies, *viz*., CHF, EUR, GBP and RUB cause changes in INR implying for an emerging inter-linkage of INR to the currencies in the advanced economies. Second, evidence of bi-directional causality between changes in the Indian Rupee and the Brazilian Real implies for a strong integration among the currencies of these two leading EMEs. Third, there is no significant causal relationship between the Japanese yen and the Indian rupee during the period under study (Table 8).

As mentioned earlier, the choice of conditional mean specification is an important challenge in tests for volatility spillovers. We estimate GARCH models for each currency with three different specifications of conditional mean, *viz*., GARCH(1,1) with simple conditional mean, GARCH(1,1)-M with conditional mean as a function of conditional variance and AR(1)-GARCH(1,1) with conditional mean incorporating one lagged mean. However, the estimated coefficients of the three different specifications suggest that there are no distinct differences among them[2]. We estimate AR(1)-GARCH(1,1) model by including a lagged dependent variable in the mean equation which is significant in case of BRL and RUB. Taking the first difference of the series eliminated unit roots in levels.

Estimated coefficients of AR(1)-GARCH(1,1) model as per the specifications mentioned in Step I are reported in Table 9. The robustness of parameters of the estimated models are checked with various diagnostics such as Schwartz Information Criterion (SIC)[3], Durbin Watson (DW) statistics and Ljung-Box (LB) Q-statistics of the residuals[4]. The ARCH parameter β_0 is statistically significant for all exchange rates implying for the presence of conditional autocorrelation in each of the currencies. The GARCH parameter γ_0 is statistically significant and very high, even close to unity for some currencies implying the persistence of volatility in daily exchange rates. Barring BRL and GBP, the dummy variable representing a break in the series due to the collapse of Lehman Brothers is found to be significant. The L-B Q-statistics for residuals at lag 10 are not very high except for the INR. However, the Q-statistics for squared residuals are found to be low indicating absence of remaining residual autocorrelation in the model.

To obtain the spillover effect, we include the squared residuals obtained from the above estimated GARCH models for each currency in the AR(1)-GARCH(1,1) model for the INR as per the specifications mentioned in Step II and re-estimated it (Table 10). The spillover coefficient φ emanating from all other currencies included in the study are found to be highly significant implying that volatilities in these currencies had a considerable impact on the volatilities in the daily exchange rate of the Indian rupee. Furthermore, the magnitude of spillover coefficient is found to be broadly same across countries implying that the extent of volatility transmitted to the Indian Rupee from leading currencies are to be similar. The other coefficients representing conditional volatility and its persistence continued to remain high and significant. However, the spillover coefficients are found to be smaller than the

[2] The estimates of GARCH (1,1) and GARCH(1,1)-M specifications are not reported here, but are available from the author on request.

[3] Models are considered to be better for lower SICs, since the tests are based on residual sum of squares.

[4] The Ljung-Box Q-statistics checks the null hypothesis that there is no remaining residual autocorrelation, for a number of lags, given the alternative that at least one of the autocorrelations is non-zero. The null hypothesis is rejected for large values of Q.

ARCH and GARCH parameters indicating that the volatility in the exchange rate of the Indian Rupee is also driven by domestic macroeconomic and other global factors along with volatility transmission.

VI. Conclusion

While there is availability of a large volume of literature in examining exchange rate volatility, research on spillover effects emanating from volatilities in major foreign currencies to the volatility in the exchange rate of the Indian Rupee is still lacking. This study makes an attempt to bridge this gap by investigating not only the own volatility factor of the Indian Rupee but also the spillover effects emanating from exchange rates of the Brazilian Real, the Russian Ruble, the South Korean Won, the Singapore Dollar, the Japanese Yen, the Swiss Franc, the British Pound Sterling and the Euro. Among the class of ARCH and GARCH models, the study employs a two-step multivariate AR(1)-GARCH(1,1) framework to examine the dynamics of exchange rate volatility and its spillovers which is also corroborated by examining simple pair-wise Granger causality tests. We found evidence of conditional autocorrelation and persistence of volatility in daily exchange rates of all nine currencies. The findings also support the view that volatilities observed in the exchange rate of the leading currencies transmit to volatility in the daily exchange rate of the Indian Rupee. However, as the spillover coefficients are smaller than the ARCH and GARCH parameters, the volatility in the exchange rate of the Indian Rupee could also be driven by domestic macroeconomic and global factors. It is also worthwhile to mention that the study can be further extended by incorporating news factor in examining intraday variations which would provide greater insights into the *heat waves* and *meteor showers* hypothesis.

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Table 1: Appreciation(+)/Depreciation(-) of Major Currencies (point-to-point, per cent)									
Period	**USDEUR**	**USDJPY**	**USDGBP**	**USDCHF**	**USDSGD**	**USDKRW**	**USDRUB**	**USDBRL**	**USDINR**
2006	11.4	-1.1	13.7	7.6	8.1	15.9	9.2	9.3	1.8
2007	10.5	6.5	1.3	7.6	6.8	5.8	7.0	20.0	12.3
2008	-4.2	23.3	-26.4	6.1	0.7	-17.4	-16.3	-23.1	-19.2
2009	2.6	-2.6	10.7	3.2	1.8	9.4	-2.1	32.7	4.9
2010	-6.6	14.7	-3.5	10.7	9.5	6.7	-1.6	5.0	4.1
2011	-3.2	5.5	-0.5	-0.3	-1.0	-2.6	-5.0	-11.0	-15.8
H1-2011	8.3	0.7	2.8	11.3	4.5	6.1	9.6	6.3	0.0
H2-2011	-10.6	4.7	-3.2	-10.4	-5.3	-8.1	-13.3	-16.3	-15.8
Source: Bloomberg and Author's calculation.									

Table 2: Descriptive Statistics – Full Sample (Jan-2005 to Dec-2011)									
	LBRL	LCHF	LEUR	LGBP	LINR	LJPY	LRUB	LKRW	LSGD
Mean	0.67	0.10	-0.30	-0.55	3.80	4.61	3.34	1.95	0.38
Std. Dev.	0.14	0.12	0.07	0.11	0.06	0.14	0.09	0.09	0.09
Skewness	0.35	-0.73	-0.21	0.07	-0.12	-0.34	0.03	0.11	-0.19
Kurtosis	2.01	2.92	2.42	1.78	2.95	1.79	2.72	2.57	2.12
Jarque-Bera	105.92	164.37	39.38	122.76	4.90	147.02	6.54	17.64	69.74
Probability	0.0	0.0	0.0	0.0	0.09	0.0	0.04	0.0	0.0
ADF (level)*	-2.36	-0.97	-1.93	-1.27	-0.47	-0.20	-1.12	-2.23	-0.87
ADF (1^{st} Diff.)*	-44.97	-42.75	-41.30	-39.92	-39.98	-44.84	-36.45	-43.10	-43.53
Nobs.	1825	1825	1825	1825	1825	1825	1825	1825	1825

Note: (1) Exchange rate is defined as units of domestic currency per one unit of US Dollar. L denotes natural logarithms.

BRL: Brazilian Real; CHF: Swiss Franc; EUR: Euro; GBP: Great Britain Pound; INR: Indian Rupee; JPY: Japanese Yen; RUB: Russian Ruble; KRW: South Korean Won; SGD: Singapore Dollar.

(2) ADF tests are estimated at maximum lag of 24 based on Schwartz information criterion. The critical values for ADF test are -3.44, -2.86 and -2.57, respectively, at 1%, 5% and 10% levels of significance.

Table 3: Descriptive Statistics – Pre-Lehman (Jan-2005 to Aug-2008)									
	LBRL	LCHF	LEUR	LGBP	LINR	LJPY	LRUB	LKRW	LSGD
Mean	0.73	0.18	-0.28	-0.64	3.76	4.73	3.28	1.95	0.44
Std. Dev.	0.14	0.07	0.08	0.05	0.05	0.05	0.06	0.08	0.07
Skewness	-0.17	-1.01	-0.66	0.34	-0.47	-0.47	-0.45	-0.30	-0.58
Kurtosis	2.35	3.37	2.46	1.96	1.96	2.15	2.07	2.30	2.36
Jarque-Bera	20.54	189.38	79.74	59.92	76.08	62.44	64.02	32.87	68.87
Probability	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ADF (level)*	-0.65	-0.61	0.10	-1.31	-0.84	-2.08	0.73	-0.49	0.59
ADF (1st Diff.)*	-31.58	-31.34	-30.58	-30.88	-29.80	-32.04	-29.94	-30.83	-23.68
Nobs.	933	933	933	933	933	933	933	933	933

Note: (1) Exchange rate is defined as units of domestic currency per one unit of US Dollar. L denotes natural logarithms.
BRL: Brazilian Real; CHF: Swiss Franc; EUR: Euro; GBP: Great Britain Pound; INR: Indian Rupee; JPY: Japanese Yen; RUB: Russian Ruble; KRW: South Korean Won; SGD: Singapore Dollar.
(2) ADF tests are estimated at maximum lag of 20 based on Schwartz information criterion. The critical values for ADF test are -3.44, -2.86 and -2.57, respectively, at 1%, 5% and 10% levels of significance.

Table 4: Descriptive Statistics – Post-Lehman (Sep-2008 to Dec-2011)									
	LBRL	LCHF	LEUR	LGBP	LINR	LJPY	LRUB	LKRW	LSGD
Mean	0.60	0.01	-0.31	-0.46	3.85	4.48	3.40	1.96	0.31
Std. Dev.	0.12	0.11	0.05	0.06	0.05	0.09	0.07	0.09	0.07
Skewness	0.99	-0.63	0.23	-0.53	0.52	0.24	-0.34	0.43	-0.17
Kurtosis	3.02	2.72	2.40	4.64	2.72	2.45	4.09	2.53	1.95
Jarque-Bera	146.56	61.13	21.69	141.89	43.03	20.0	61.20	35.52	45.55
Probability	0.0	0.0	0.0	0.0	0.09	0.0	0.04	0.0	0.0
ADF (level)*	-1.93	-1.15	-2.88	-4.03	-1.35	-1.79	-3.15	-2.29	-0.87
ADF (1st Diff.)*	-31.71	-29.52	-28.48	-27.01	-27.56	-31.37	-25.13	-30.11	-30.52
Nobs.	892	892	892	892	892	892	892	892	892

Note: (1) Exchange rate is defined as units of domestic currency per one unit of US Dollar. L denotes natural logarithms.
BRL: Brazilian Real; CHF: Swiss Franc; EUR: Euro; GBP: Great Britain Pound; INR: Indian Rupee; JPY: Japanese Yen; RUB: Russian Ruble; KRW: South Korean Won; SGD: Singapore Dollar.
(2) ADF tests are estimated at maximum lag of 20 based on Schwartz information criterion. The critical values for ADF test are -3.44, -2.86 and -2.57, respectively, at 1%, 5% and 10% levels of significance.

Table 5: Correlation Coefficients – Full Sample (Jan-2005 to Dec-2011)

	LBRL	LCHF	LEUR	LGBP	LINR	LJPY	LRUB	LKRW	LSGD
LBRL	1.0								
LCHF	0.76	1.0							
LEUR	0.69	0.62	1.0						
LGBP	-0.13	-0.42	0.18	1.0					
LINR	0.16	-0.20	0.29	0.79	1.0				
LJPY	0.53	0.88	0.30	-0.75	-0.50	1.0			
LRUB	0.13	-0.21	0.37	0.86	0.79	-0.58	1.0		
LKRW	0.67	0.56	0.77	0.46	0.55	0.17	0.61	1.0	
LSGD	0.87	0.95	0.64	-0.40	-0.13	0.81	-0.13	0.58	1.0

BRL: Brazilian Real; CHF: Swiss Franc; EUR: Euro; GBP: Great Britain Pound; INR: Indian Rupee; JPY: Japanese Yen; RUB: Russian Ruble; KRW: South Korean Won; SGD: Singapore Dollar.

Note: Exchange rate is defined as units of domestic currency per one unit of US Dollar. L denotes natural logarithms.

Table 6: Correlation Coefficients – Pre-Lehman (Jan-2005 to Aug-2008)

	LBRL	LCHF	LEUR	LGBP	LINR	LJPY	LRUB	LKRW	LSGD
LBRL	1.0								
LCHF	0.69	1.0							
LEUR	0.81	0.96	1.0						
LGBP	0.63	0.68	0.82	1.0					
LINR	0.64	0.60	0.72	0.71	1.0				
LJPY	0.06	0.68	0.48	0.11	0.25	1.0			
LRUB	0.90	0.88	0.96	0.83	0.68	0.27	1.0		
LKRW	0.74	0.94	0.99	0.86	0.69	0.47	0.94	1.0	
LSGD	0.91	0.88	0.95	0.78	0.65	0.30	0.99	0.93	1.0

BRL: Brazilian Real; CHF: Swiss Franc; EUR: Euro; GBP: Great Britain Pound; INR: Indian Rupee; JPY: Japanese Yen; RUB: Russian Ruble; KRW: South Korean Won; SGD: Singapore Dollar.

Note: Exchange rate is defined as units of domestic currency per one unit of US Dollar. L denotes natural logarithms.

Table 7: Correlation Coefficients – Post-Lehman (Sep-2008 to Dec-2011)									
	LBRL	LCHF	LEUR	LGBP	LINR	LJPY	LRUB	LKRW	LSGD
LBRL	1.0								
LCHF	0.68	1.0							
LEUR	0.51	0.27	1.0						
LGBP	0.50	0.09	0.84	1.0					
LINR	0.63	0.15	0.63	0.76	1.0				
LJPY	0.23	0.72	-0.36	-0.55	-0.37	1.0			
LRUB	0.45	0.06	0.72	0.88	0.78	-0.52	1.0		
LKRW	0.85	0.63	0.75	0.76	0.71	0.04	0.73	1.0	
LSGD	0.78	0.94	0.20	0.11	0.27	0.70	0.14	0.69	1.0

BRL: Brazilian Real; CHF: Swiss Franc; EUR: Euro; GBP: Great Britain Pound; INR: Indian Rupee; JPY: Japanese Yen; RUB: Russian Ruble; KRW: South Korean Won; SGD: Singapore Dollar

Note: Exchange rate is defined as units of domestic currency per one unit of US Dollar. L denotes natural logarithms.

Table 8: Granger Causality Test – Full Sample (Jan-2005 to Dec-2011)		
Null Hypothesis	**F-Statistics**	**Probability**
BRL does not Granger cause INR	47.95	0.0
INR does not Granger cause BRL	2.63	0.07
CHF does not Granger cause INR	11.85	0.0
INR does not Granger cause CHF	0.22	0.80
EUR does not Granger cause INR	31.76	0.0
INR does not Granger cause EUR	0.14	0.87
GBP does not Granger cause INR	9.46	0.0
INR does not Granger cause GBP	1.70	0.18
JPY does not Granger cause INR	1.27	0.28
INR does not Granger cause JPY	0.15	0.86
RUB does not Granger cause INR	15.27	0.0
INR does not Granger cause RUB	1.22	0.30
KRW does not Granger cause INR	37.69	0.0
INR does not Granger cause KRW	1.19	0.30
SGD does not Granger cause INR	35.58	0.0
INR does not Granger cause SGD	1.01	0.37

Note: Granger causality tests are based on two lags.

Table 9: Estimated Coefficients of AR(1)-GARCH(1,1) Model									
Parameter	BRL	CHF	EUR	GBP	INR	JPY	RUB	KRW	SGD
c_0	-0.0005*	-0.0002	-0.0001	-1.79E-05	1.17E-05	9.47E-06	-0.0001**	-9.61E-05*	-0.0002*
	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(7.36E-05)	(0.0001)	(7.05E-05)	(0.0002)	(6.41E-05)
η_0	-0.05**	-0.009	0.02	0.03	0.03	-0.02	0.11*	0.005	0.01
	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)
α_0	1.71E-06*	3.21E-07*	1.61E-07**	3.19E-07*	2.69E-07*	1.26E-06*	1.43E-07*	6.59E-07*	1.06E-07*
	(3.63E-07)	(1.20E-07)	(8.18E-08)	(1.27E-07)	(3.62E-08)	(2.99E-07)	(3.15E-05)	(2.41E-07)	(3.35E-08)
β_0	0.14*	0.05*	0.03*	0.04*	0.1*	0.06*	0.07*	0.04*	0.04*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
γ_0	0.85*	0.94*	0.96*	0.95*	0.87*	0.9*	0.9*	0.94*	0.94*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
δ_0	4.98E-07	3.35E-07***	2.58*	2.21E-07	5.87E-07*	9.21E-07*	1.06E-06*	1.16E-06*	1.46E-07*
	(5.07E-07)	(1.69)	(1.63E-07)	(1.58E-07)	(1.55E-07)	(2.43E-07)	(1.72E-07)	(4.37E-07)	(3.85E-08)
SIC	-6.59	-7.14	-7.34	-7.45	-8.36	-7.25	-8.21	-6.81	-8.57
DW	2.01	1.98	1.98	1.91	1.93	2.06	1.89	2.03	2.06
L-B Q-stat. Residuals	9.24	4.85	5.69	3.38	22.64	10.77	8.50	11.56	10.63
L-B Q-stat. Sqr. Res.	10.81	4.80	11.96	9.44	6.95	3.53	4.60	9.01	3.62
Nobs.	1823	1823	1823	1823	1823	1823	1823	1823	1823

Note: (1) Figures in parentheses are estimated standard errors. *, ** and *** denote significance at 1%, 5% and 10%, respectively.
(2) Ljung-Box Q-statistics are reported for lag 10.

Table 10: Volatility Transmission Model – AR(1)-GARCH(1,1)								
Parameter	BRL	CHF	EUR	GBP	JPY	RUB	KRW	SGD
c_1	1.84E-06 (7.27E-05)	1.05E-05 (7.39E-05)	1.75E-06 (7.34E-05)	1.41E-05 (7.21E-05)	2.03E-05 (6.83E-05)	-1.69E-06 (7.36E-05)	-2.88E-06 (7.32E-05)	1.29E-08 (7.20E-05)
η_1	0.02 (0.02)	0.03 (0.02)	0.03 (0.02)	0.02 (0.02)	0.03 (0.02)	0.13 (0.02)	0.02 (0.02)	0.03 (0.03)
α_1	1.64E-07* (4.28E-08)	1.57E-07* (4.10E-08)	1.20E-07* (4.45E-08)	2.29E-08 (4.97E-08)	-3.84E-08 (3.22E-08)	3.01E-07* (4.48E-08)	8.75E-08*** (5.19E-08)	1.77E-07* (4.23E-08)
β_1	0.12* (0.01)	0.09* (0.01)	0.11* (0.01)	0.11* (0.01)	0.11* (0.01)	0.12* (0.01)	0.11* (0.01)	0.15* (0.01)
γ_1	0.83* (0.01)	0.88* (0.01)	0.86* (0.01)	0.85* (0.01)	0.86* (0.01)	0.83* (0.01)	0.85* (0.01)	0.79* (0.02)
φ_i	0.01* (0.001)	0.003* (0.001)	0.01* (0.002)	0.01* (0.002)	0.01* (0.001)	0.02* (0.004)	0.01* (0.001)	0.06* (0.01)
δ_1	8.21E-07* (1.80E-07)	4.59E-07* (1.46E-07)	4.84E-07* (1.61E-07)	5.46E-07* (1.65E-07)	5.63E-07* (1.44E-07)	3.76E-07** (1.79E-07)	3.20E-07* (1.57E-07)	8.05E-07* (2.08E-07)
SIC	-8.38	-8.36	-8.37	-8.37	-8.39	-8.37	-8.37	-8.39
DW	1.91	1.92	1.92	1.92	1.92	1.92	1.92	1.92
L-B Q-stat. Residuals	23.23	22.20	22.99	23.77	23.55	22.87	23.52	23.16
L-B Q-stat. Sqr. Res.	6.20	6.62	6.24	5.72	5.10	6.81	6.36	6.32
Nobs.	1823	1823	1823	1823	1823	1823	1823	1823
Note: (1) Figures in parentheses are estimated standard errors. *, ** and *** denote significance at 1%, 5% and 10%, respectively. (2) Ljung-Box Q-statistics are reported for lag 10.								

Chart 1: Exchange Rate of Major Currencies *vis-à-vis* the US Dollar