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METEOR SHOWERS OR HEAT WAVES? HETEROSKEDASTIC INTRA-DAILY VOLATILITY IN THE FOREIGN EXCHANGE MARKET

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This paper seeks to explain the causes of volatility clustering in exchange rates. Careful examination of intra-daily exchange rates provides a test of two hypotheses—heat waves and meteor showers. The heat wave hypothesis is that the volatility has only country-specific autocorrelation. Alternatively, the meteor shower is a phenomenon of intra-daily volatility spillovers from one market to the next. Using the GARCH model to specify the heteroskedasticity across intra-daily market segments, we find that the empirical evidence is generally against the null hypothesis of the heat wave. Using a volatility type of vector autoregression we examine the impact of news in one market on the time path of per-hour volatility in other markets.

KEYWORDS: ARCH, volatility, exchange rates, GARCH, intra-daily, policy coordination.

1. INTRODUCTION

IT IS WELL KNOWN that exchange rates approximately follow a martingale process so that future changes are essentially unpredictable on the basis of publicly available information.[2] This finding is in accord with the efficient market hypothesis as described by Fama (1970).[3] It has also long been known that exchange rates exhibit volatility clustering so that large changes tend to be followed by large changes of either sign and periods of tranquility alternate with periods of high volatility.[4] Recently, many investigators have modelled the dynamic process of the conditional volatility using ARCH and GARCH models. For example, Engle and Bollerslev (1986), Domowitz and Hakkio (1985), Diebold and Nerlove (1988), Hsieh (1985), and McCurdy and Morgan (1988) have all documented the forecastability of volatility. The explanation for such volatility processes must lie either in the arrival process of news or in market dynamics in response to the news. If information comes in clusters, then the asset returns or prices may exhibit ARCH behavior even if the market perfectly and instantaneously adjusts to the news. Alternatively, traders with heterogeneous priors and private information may take some hours of trading, after a shock, to have

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[2] For example, Meese and Rogoff (1983a, b) tested the random walk hypothesis against other forecasting formulae and found the random walk hypothesis to be as good as others. Ito and Roley (1987) and Ito (1987) showed how the exchange rate responded to various news in the different markets around the clock.

[3] This is true if traders are risk neutral and interest rate differentials are zero. In fact, the intra-daily interest rate differentials are negligible in our studies.

[4] Fama's observation on volatility clustering is summarized as follows: "large daily price changes tend to be followed by large daily changes. The signs of the successor changes are apparently random, however, which indicates that the phenomenon represents a denial of the random walk model but not of the market efficiency hypothesis. Nevertheless, it is interesting to speculate why the phenomenon might arise." (Fama (1970, p. 396).)

expectational differences resolved. In either case, market dynamics lead to a continuation of volatility. In either case, market expectation based on public information could at every time point be unbiased, so in that sense it still accords with market efficiency.

As an example of market dynamics, Kyle (1985) (see also Admati and Pfleiderer (1988)) constructs a dynamic model of insider trading with sequential auctions where one risky asset is exchanged for a risk free asset among three kinds of investors: a single insider, uninformed noise traders, and market makers. In the continuous auction equilibrium, the price follows a Brownian motion and the insider private information is gradually disseminated into prices so that it is still consistent with the semi-strong form of market efficiency but not the strong form. Since the price does not fully incorporate this private information about the fundamental value until the end of trading, this model provides a possible explanation for volatility spillovers. In this context, the finding of volatility spillovers is consistent with a failure of strong form market efficiency.

Using meteorological analogies, we suppose that news follows a process like a *heat wave* so that a hot day in New York is likely to be followed by another hot day in New York but not typically by a hot day in Tokyo. The alternative analogy is a *meteor shower* which rains down on the earth as it turns. A meteor shower in New York will almost surely be followed by one in Tokyo. To anticipate our conclusion, volatility appears to be a meteor shower rather than a heat wave.

In this paper, careful examination of intra-daily exchange rates provides a laboratory where the volatility process can be examined. Using the set-up of Ito and Roley (1987) and Ito (1987), we decompose the daily change in exchange rates into the parts occurring while each of the major markets is open. In this paper we ask whether news in the New York market can predict volatility in the Tokyo market several hours later.

The heat wave hypothesis is consistent with a view that major sources of disturbances are changes in country-specific fundamentals, and that one large shock increases the conditional volatility but only in that country. If the policy switch of the Federal Reserve, revealed or suspected toward the end of day t, is the source of volatility on day t, then a new piece of information, such as how serious the Fed is about lowering the interest rate, would not be revealed until the New York business hours of day $t+1$. Therefore, the conditional volatility of the New York market on day $t+1$ will increase, but not the conditional volatility of the Tokyo or European markets. For example, Ito (1987) found that immediately after the Group of Five agreement of September 1985, most yen appreciation took place in the New York market due to the surprise intervention by the New York Fed, while a sharp appreciation in late October was caused by a surprise increase of the interest rate, revealed over a week, by the Bank of Japan and took place in the Tokyo market only. These are clear-cut examples of country-specific news on the fundamentals.

The meteor shower hypothesis can be illustrated for money supply announcements. When the monetary supply statistics are announced in New York at 4:10

p.m. of Thursday, there are less than thirty minutes to trade actively in New York. If all traders do not share a common belief about the meaning of the announced money supply, then it takes a few hours of actual trading to settle the differences in traders' priors. Ito and Roley (1987) showed evidence of the spillovers into the Pacific market after weekly money supply announcements when the Fed targeted the money growth, but they did not look at volatility spillovers.

Meteor showers could also be consistent with failures of market efficiency. For example some types of technical analysis behavior could have this characteristic. Suppose that there was a large yen appreciation in the Tokyo market. If the shock creates the expectation of more appreciation, i.e., a bandwagon, then speculation may take place in the European markets of the same day and not wait until the Tokyo market of the next day. Put differently, the conditional volatility will increase for all markets, not just for the market domestic to the shock.

Another interpretation of the meteor shower, however, is cooperative or competitive monetary policies. If the policy switch by the Fed increases the uncertainties of the monetary stance of the Bank of Japan, or vice versa, then this would show up as the meteor shower. In this interpretation, neither weak nor strong form market efficiency is violated.

The remainder of this paper is organized as follows: ARCH models used for the analysis and for this volatility modelling are presented in Section 2. Because of the rich dynamics of the volatility process we can trace out the effects of news from one market on the volatility in other markets using a technique which is like a vector autoregression for volatility. Section 3 reports the data summary and the estimation of a daily model with the yen/dollar exchange rate data since the Group of Five meeting of September, 1985. Section 4 is devoted to tests of the heat wave vs. meteor shower hypotheses. Our statistical tests lead to a rejection of the heat waves hypothesis. In Section 5, impulse responses of volatility across market segments are defined, described, and interpreted. Section 6 investigates the robustness of the model with respect to alternative specifications. The day-of-the-week effects and holiday effects are considered. The final section summarizes the main conclusions of this paper.

2. ECONOMETRIC SPECIFICATION

To model the dynamic process of intra-daily volatility a series of ARCH and GARCH models are formulated following Engle (1982) and Bollerslev (1986). We assume that there are n nonoverlapping markets within a day with market 1 open first. Since major foreign market segments in the world open and close sequentially, the volatility originating from the previous open market segments can be treated as predetermined variables. That is, the information set for market 2 includes today's information on market 1 as well as all of yesterday's news. By letting $\varepsilon_{i,t}$ be the intra-daily exchange rate change divided by the square root of business hours in market i on date t, we can modify the GARCH model as a vector autoregression for per-hour volatility:

$$\text{(1)} \qquad \varepsilon_{i,t}|\psi_{i,t} \sim \mathcal{N}(0, h_{i,t}) \quad \text{for} \quad i = 1, 2, \dots, n,$$

$$h_{i,t} = \omega_i + \beta_{ii} h_{i,t-1} + \sum_{j=1}^{i-1} \alpha_{ij} \varepsilon_{j,t}^2 + \sum_{j=i}^{n} \alpha_{ij} \varepsilon_{j,t-1}^2,$$

where $\psi_{i,t}$ is the information set for market i on date t, which includes the past information on date $t-1$ and the current information from market 1 to market $i-1$ on date t, i.e., $\psi_{i,t} = \{\varepsilon_{i-1,t}, \varepsilon_{i-2,t}, \dots, \varepsilon_{1,t}\} \cup \psi_{n,t-1}$, and $\psi_{n,t-1}$ denotes the sequence of information sets generated by $\{\varepsilon_{1,k}, \dots, \varepsilon_{n,k}\}_{k=1}^{t-1}$. Several assumptions are made in this setting. First, we assume market efficiency which implies that intra-daily exchange rate changes are distributed with mean zero. This assumption is tested in Section 6. Clearly, the assumption that $\varepsilon_{i,t}$ and $\varepsilon_{j,t}$ for $i \neq j$ are uncorrelated follows the first assumption.[5] Third, we set $\varepsilon_{j,t-1}^2 = 0$ for $j = i+1, \dots, n$, or $\varepsilon_{j,t}^2 = 0$ for $j = 1, \dots, i-1$ if market j is closed because of a holiday on date t or $t-1$. This choice follows from the view that the conditional variance tends to change upon the arrival of the new information and that little or no new information is revealed during a holiday.[6]

Let us denote the variance parameter vector for market i as a $(2+n) \times 2$ vector $\theta_i' = (\omega_i, \beta_{ii}, \alpha_{i1}, \alpha_{i2}, \dots, \alpha_{in})$. We can combine these parameters for all markets into an $n(2+n) \times 1$ vector $\theta' = (\theta_1', \dots, \theta_n')$. Then the log-likelihood function of equation (1) conditional on the initial values can be expressed as

$$\text{(2)} \qquad L(\theta) = \sum_{t=1}^{T} L_t(\theta) = \sum_{t=1}^{T} \sum_{i=1}^{n} \ell_{i,t}(\theta_i), \quad L_t(\theta) = \sum_{i=1}^{n} \ell_{i,t}(\theta_i),$$

and

$$\ell_{i,t}(\theta_i) = -1/2 \log h_{i,t} - 1/2\left(\varepsilon_{i,t}^2 / h_{i,t}\right)$$

where a constant has been omitted. The estimation and test procedures are simply extended from Engle and Bollerslev. Letting $w_{i,t}' = (1, h_{i,t-1}, \varepsilon_{1,t}^2, \dots, \varepsilon_{i-1,t}^2, \varepsilon_{i,t-1}^2, \dots, \varepsilon_{n,t-1}^2)$, the maximum likelihood estimators (MLE) solve the first order conditions of equation (2):

$$\text{(3)} \qquad \partial L(\theta)/\partial\theta_i = 1/2 \sum_{t=1}^{T} h_{i,t}^{-1}\, \partial h_{i,t}/\partial\theta_i \left(\varepsilon_{i,t}^2/h_{i,t} - 1\right) = S(\theta_i)'\iota$$

and

$$\partial h_{i,t}/\partial\theta_i = w_{i,t} + \beta_{ii}\, \partial h_{i,t-1}/\partial\theta_i \quad \text{for} \quad i = 1, 2, \dots, n$$

where $S(\theta_i)$ is a $T \times (n+2)$ matrix with typical element $[S(\theta_i)]_{tj} = \partial \ell_t(\theta)/\partial\theta_{ij}$

[5] From an econometric viewpoint, innovations should not be serially correlated in ARCH models; otherwise they can be forecast by using the past information and then the conditional mean will not be zero. In Section 6, robustness checks are also implemented to justify this assumption.

[6] For example, as suggested by French and Roll (1986), the volatility of stock prices can be caused by the arrival of new information or mispricing. The volatility of stock prices is relatively lower in nontrading hours.

and ι is a $T \times 1$ unit vector. The numerical solution to iterative estimation procedures can be obtained by using the Berndt, Hall, Hall, and Hausman (1974) (BHHH) algorithm. If the log-likelihood function is correctly specified, then the information matrix is equal to $E(S(\theta)'S(\theta)/T)$, where $S(\theta) = [\partial \ell_t(\theta)/\partial \theta_{ij}]_{T \times n(n+2)}$. Since the cross partial derivatives with respect to θ_i and θ_j, for $i \neq j$, equal zero, the information matrix is block diagonal with respect to θ_i. Therefore, the single equation estimation of the GARCH model can be performed on each market to yield consistent and efficient estimators (see Pagan (1986)). Under suitable regularity and moment conditions, it can be shown that[7]

$$(4) \qquad \left(S(\theta_i^*)'S(\theta_i^*)\right)^{1/2}\left(\theta_i^* - \theta_i^0\right) \sim \mathcal{N}(0, I)$$

where θ_i^* is a vector of the maximum likelihood estimators obtained from the BHHH algorithm and θ_i^0 is a vector of the true value of the parameters.

The strategy is to formulate ARCH models for each segment of the market which depend upon past information from this market and past information from other markets. Now the heat wave hypothesis is the null hypothesis of $\alpha_{ij} = 0$ jointly for $j \neq i$. The meteor shower hypothesis is the alternative.

The second purpose of our paper is to develop techniques for examining the dynamic market reaction to the country-specific news. We compute the expected per-hour variance in one market several periods in the future as a function of the shock to a different market. Introducing vector notation so that all equations can be solved jointly, let $\boldsymbol{h}_t = (h_{1,t}, \dots h_{n,t})'$ represent the vector of conditional heteroskedasticity of all the markets on date t, and let $\boldsymbol{\eta}_t = (\varepsilon_{1,t}^2, \dots, \varepsilon_{n,t}^2)'$ be the vector of per-hour squared innovations or news on this date. Then equation (1) can be written as of date $t+1$ as

$$(5) \qquad \boldsymbol{h}_{t+1} = \boldsymbol{\omega} + B\boldsymbol{h}_t + A\boldsymbol{\eta}_{t+1} + C\boldsymbol{\eta}_t$$

where $\boldsymbol{\omega}$ is a vector of intercepts, and

$$A = \begin{pmatrix} 0 & 0 & 0 & \dots & 0 \\ \alpha_{21} & 0 & 0 & \dots & 0 \\ \vdots & & & & \vdots \\ \alpha_{n1} & \alpha_{n2} & & \dots & 0 \end{pmatrix}, \quad B = \begin{pmatrix} \beta_{11} & 0 & 0 & \dots & 0 \\ 0 & \beta_{22} & 0 & \dots & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & & \dots & \beta_{nn} \end{pmatrix},$$

$$C = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1n} \\ 0 & \alpha_{22} & \dots & \alpha_{2n} \\ \vdots & & & \vdots \\ 0 & \dots & \dots & \alpha_{nn} \end{pmatrix}.$$

Letting $\boldsymbol{h}_{t+s/nt} \equiv E(\boldsymbol{h}_{t+s} | \psi_{n,t})$ and taking the iterated expectation, i.e.,

[7] Weiss (1986) proves the consistency and asymptotic normality of maximum likelihood estimates without assuming the normality of ε_t and shows the sufficient conditions requiring the following conditions: the finite fourth moment of ε_t, the true parameters interior to the parameter space, and the nonsingularity of S′S.

$E(E(\varepsilon^2_{i,t+1}|\psi_{i,t+1})|\psi_{n,t}) = E(h_{i,t+1}|\psi_{n,t})$, this becomes

$$\boldsymbol{h}_{t+1/nt} = \boldsymbol{\omega} + B\boldsymbol{h}_t + A\boldsymbol{h}_{t+1/nt} + C\boldsymbol{\eta}_t, \tag{6}$$

and for general s step ahead predictions

$$(I - A)\boldsymbol{h}_{t+s/nt} = \boldsymbol{\omega} + (B + C)\boldsymbol{h}_{t+s-1/nt} \quad \text{for} \quad s \geqslant 2. \tag{7}$$

Since $\psi_{k,t} \subset \psi_{n,t}$ for $k = 1, 2, \ldots, n$, by the similar arguments, we can rewrite equation (7) as the more general form:

$$(I - A)\boldsymbol{h}_{t+s/kt} = \boldsymbol{\omega} + (B + C)\boldsymbol{h}_{t+s-1/kt}. \tag{8}$$

If the process is stationary, it will have an unconditional variance given by

$$\boldsymbol{h} \equiv \lim_{s \to \infty} \boldsymbol{h}_{t+s/nt}$$

which therefore is

$$\boldsymbol{h} = (I - A - B - C)^{-1}\boldsymbol{\omega}.$$

A necessary and sufficient condition for this limit to exist is that all the eigenvalues of $(I - A)^{-1}(B + C)$ lie inside the unit circle. A necessary condition for the stationarity is that the products of $\alpha_{ii} + \beta_{ii}$, $i = 1, \ldots, n$, i.e. $\prod_{i=1}^{n}(\alpha_{ii} + \beta_{ii})$, are less than one.

Letting $R_{ik}(s)$ be defined as the impulse response of per-hour volatility of market i to the squared innovation of market k, which is

$$R_{ik}(s) \equiv \partial h_{i,t+s|kt} / \partial \varepsilon^2_{k,t} \qquad (i, k = 1, 2, \ldots, n \text{ and } s \in N \cup \{0\}).$$

Taking derivatives of equation (8), we can obtain $R_{ik}(s)$ by recursively solving the following form:

$$(I - A)\boldsymbol{R}_k(s) = (B + C)\boldsymbol{R}_k(s - 1) \quad \text{for} \quad s \geqslant 2 \tag{9}$$

where $\boldsymbol{R}_k(s) = [R_{ik}(s)]_{n \times 1}$. If the process is stationary, then $\lim_{s \to \infty} \boldsymbol{R}_k(s) = 0$. By the means of computer simulation, we can easily trace out the impact of the per-hour volatility in one market on the time path of per-hour volatility of the other markets and investigate how fast it dies out.

3. THE DATA SUMMARY AND THE DAILY MODEL

3.1. *Data Summary*

We use in this paper the intra-daily yen/dollar exchange rate from October 3, 1985 to September 26, 1986 (see data appendix for more detail). This one-year period starts after the Group of Five meeting in New York. As analyzed in Ito (1987), economic news plays an important role in determinants of the exchange rate dynamics during this period. Ito (1987) only identifies the five waves of exchange rate fluctuations by looking at major news in the respective markets without analyzing the effect of country-specific news on the volatility of intra-daily exchange rates. Thus, we still have little solid evidence on how fundamental news induced per-hour volatility in the respective markets and how well the market

TABLE I
DATA SUMMARY[a]

Market Variable	Tokyo *TOKYO*	Europe *EUROP*	New York *NYORK*	Pacific *PACIF*
Mean	−0.0209	−0.1066	−0.0533	−0.0589
	(0.6134)	(0.0163)	(0.2687)	(0.0747)
Variance	0.4208	0.4643	0.5743	0.2581
Per-Hour Var[e]	0.0647	0.0663	0.0766	0.0886
Skewness[b]	−0.7730	−0.2530	−0.1825	0.0438
	(0.0000)	(0.1147)	(0.2444)	(0.7848)
Kurtosis[b,c]	3.3725	2.9570	1.8182	2.5275
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
$Q(12)$[d]	10.6455	7.7998	14.6074	11.5392
	(0.5595)	(0.8006)	(0.2636)	(0.4834)
$Q(24)$[d]	17.9575	22.1628	37.6039	21.4578
	(0.8051)	(0.5696)	(0.0380)	(0.6116)
Nobs	245	236	247	236

[a] Asymptotic p-values in parentheses.
[b] Two-tailed test under null hypothesis of normal distribution; see Kendall and Stuart (1958).
[c] Excess kurtosis adjusted to the standard normal distribution.
[d] $Q(12)$ and $Q(24)$ denote the Box-Pierce tests for up to 12th and 24th serial correlations respectively.
[e] Business hours in the Pacific, Tokyo, Europe, and New York markets are about 3, 6.5, 7, and 7.5, respectively. This assumes no volatility on the weekends.
DEFINITIONS: $TOKYO(t) = TKC(t) - TKO(t)$; $NYORK(t) = NYC(t) - NYO(t)$; $EUROP(t) = NYO(t) - TKC(t)$; $PACIF(t) = TKO(t) - NYC(t-1)$.

adjusts to new information. The disaggregation of market segments is a primary step in understanding the role of news in the determinants of per-hour volatility. Here, we consider four major market segments. We denote the change between the opening and closing prices in Tokyo as the "TOKYO" market segment. Since there is a two and a half hour (or three and a half hour during daylight savings time) interval from the New York close to the Tokyo open, we can safely assume that the Japanese news is the main cause of the TOKYO change. Although there is little trading between the New York close and the Tokyo open, we label this as a separate market segment denoted as "PACIFIC." The "NEW YORK" market segment is simply the change between the open and the close in New York. In spite of the overlap between the afternoon hours of the London market and the early morning hours of the New York market, the NEW YORK segment mainly reflects the relevant news originating in the U.S. Finally, we define the European market, "EUROPE", as the interval between the Tokyo close and New York open.[8] The per-hour volatility in one particular market is the squared intra-daily changes over business hours in this market.

Table I summarizes the relevant statistics describing our data set. We can compare these statistics with those of Ito and Roley (1987) for the period January, 1980 to September, 1985. The absolute means are relatively higher in the later period than in the earlier period. However, the variances (except the Pacific market) are lower in the later period. The per-hour volatility is approximately

[8] Here, we use the same definitions of major market segments as Ito and Roley (1987). See Ito and Roley (1987) and Ito (1988) for some caveats when using the above definitions.

0.0886, 0.0647, 0.0663, 0.0766 in the Pacific, Tokyo, European, and New York markets implying that Tokyo and Europe are the least volatile markets per hour. This calculation is based on the assumption of no volatility on weekends. Alternatively, if information arises on weekends, then the per-hour volatility in the Pacific will be reduced to 0.0222. Third, the excess kurtosis in the four markets are significantly greater than zero, indicating a fat-tailed distribution. The skewness statistics are not significantly different from zero except in the Tokyo market, revealing a symmetric distribution. Although the raw Box-Pierce statistics are upward biased in the presence of ARCH effects as pointed out by Diebold (1987), the Box-Pierce statistics are generally insignificant and therefore show no evidence of serial correlation. Together with insignificant means (except in the European market), the statistics may suggest a random process with GARCH disturbances in the foreign exchange markets.

3.2. *The Daily Model*

Most empirical papers studying the effect of news in the first moment (conditional mean equation) measure the change over 24 hours (from a closing rate to a closing rate). To compare our data with the models in the literature, we begin by investigating the per-hour volatility of *daily* exchange rate changes in the New York and Tokyo markets, because those are the only two markets with opening and closing rates. We denote the per-hour daily volatility in the Tokyo and New York markets as TK24 and NY24 respectively. The estimated results of GARCH(1,1) are presented in the first and fourth columns of Table II respec-

TABLE II

ESTIMATES AND TESTS OF DAILY, HEAT WAVE, AND FOREIGN METEOR SHOWER MODELS

$$\varepsilon_{i,t} | \psi_{i,t} \sim N(0, h_{i,t})$$
$$h_{i,t} = \omega_i + \alpha_{ii}\varepsilon^2_{i,t-1} + \beta_{ii}h_{i,t-1} + \gamma_i\eta^2_{i,t-1}$$

Market	Tokyo			New York		
$\varepsilon_{i,t}$	*TK*24	*TOKYO*	*TOKYO*	*NY*24	*NYORK*	*NYORK*
Constant	0.0062[b]	0.0030	−0.0016[a]	0.0026	0.0033	−0.0018[a]
	(0.0027)[d]	(0.0019)	(0.0006)	(0.0147)	(0.0023)	(0.0005)
$\varepsilon^2_{i,t-1}$	0.2177[a]	0.0412[b]	−0.0515[a]	0.0061	0.0809[a]	−0.00966
	(0.0561)	(0.0203)	(0.0077)	(0.0214)	(0.0322)	(0.00950)
$h_{i,t-1}$	0.7184[a]	0.9115[a]	0.9675[a]	0.9595[a]	0.8751[a]	0.98617[a]
	(0.0633)	(0.0486)	(0.0107)	(0.2145)	(0.0440)	(0.00819)
$\eta^2_{i,t-1}$			0.0759[a]			0.0432[a]
			(0.0107)			(0.0066)
L	−23.9956	−7.5194	1.1136	−32.2032	−28.0006	−14.7057
$LR(1)$[c]			17.2660[a]			26.5898[a]

[a] Indicates significance at a 1% level.
[b] Indicates significance at a 5% level.
[c] Likelihood ratio test for the null hypothesis $\gamma_i = 0$: $\sim \chi^2(1)$.
[d] Standard errors in parentheses.

DEFINITIONS: $TK24(t) = (TKC(t) - TKC(t-1))/SQRT(24)$; $NY24(t) = (NYC(t) - NYC(t-1))/SQRT(24)$; $TOKYO(t) = (TKC(t) - TKO(t))/SQRT(6.5)$; $NYORK(t) = (NYC(t) - NYO(t))/SQRT(7.5)$; $\eta_{TOKYO}(t-1) = (TKO(t) - TKC(t-1))/SQRT(17.5)$; $\eta_{NYORK}(t-1) = (NYO(t) - NYC(t-1))/SQRT(16.5)$.

tively. Most of the estimated coefficients are significant at a 5% level and they reflect a strong GARCH effect. The sum of coefficients in the conditional variance equation is only slightly less than 1.0 and maybe reveals the integrated GARCH process as described in Engle and Bollerslev (1986). The per-hour daily innovation in Tokyo has a larger impact on the conditional volatility in the future. They are similar to results in Diebold and Nerlove (1988) and McCurdy and Morgan (1988). In general, the per-hour volatility of the daily change in the yen/dollar exchange rate is serially correlated and there is persistent volatility conditional on the current information.

These results leave unanswered the questions posed in the introduction. During the 24 hour period, information from all countries is aggregated. Thus it is not possible to separate the sources of the information and the causes of the price and volatility changes. In particular, yesterday's change has a major impact on today's volatility, but it is not clear whether this is due to daily serial correlation in the country-specific news or volatility spillovers between different markets within a day.

4. ESTIMATES AND TESTS OF METEOR SHOWERS VS HEAT WAVES

4.1. *Heat Waves*

In the following subsection, our attention is focused first on the heat wave model of per-hour volatility in New York and Tokyo only. These are the two markets with the well defined opening and closing rates. In this case, the conditional variance of the change in one market depends solely upon the past shocks in this market. The results are shown for the Tokyo and New York markets in the second and fifth rows of Table II. The results again suggest a positive and significant effect of yesterday's change on today's volatility as well as the possibility of a unit root in the variance process which says that these shocks last forever.

4.2. *Meteor Showers with Foreign News*

For the two domestic markets, Tokyo and New York, the per-hour squared change between the opening and closing quotes is a reflection of the domestic volatility. The per-hour squared change between the closing rate at the previous period and opening rate at this period measures the effect of the foreign volatility, which aggregates the effects from the other markets. The heat wave hypothesis is equivalent to a zero coefficient on the foreign market term.

The test against the meteor shower hypothesis which aggregates all foreign news, is conducted by the likelihood ratio test described in Section 2. The results shown in Table II indicate that the null hypothesis of heat waves can be rejected at least at a 5% significance level in both the Tokyo and New York markets.

Table II also presents estimates of the meteor shower model aggregating the foreign news. The striking feature of these estimates is the finding that the foreign news is more important than yesterday's domestic news. The result is much like a Granger causality test for variances where the own lag is significant until the intervening variables are introduced. The constants in the conditional variance become negative which implies that the unconditional or conditional variances could be negative depending upon the relative magnitude of foreign news to the domestic news and constant term in the foreign news equation. On the whole, we can conclude that there are volatility spillovers which may be interpreted either as a lack of strong form efficiency, or as evidence for important, potential international policy coordination that implies cross country news autocorrelation.

Although the heat wave hypothesis is soundly rejected, this specification does not allow us to pinpoint the source of the volatility. In the next section we decompose the foreign news into its component market segments and therefore can trace the impact of a news shock in one market through the system.

4.3. *Meteor Showers with Country-Specific News*

In this subsection, overnight changes are disaggregated into three different segments. The heat wave hypothesis is equivalent to the joint restriction of

TABLE III

ESTIMATES AND TESTS OF METEOR SHOWERS WITH COUNTRY-SPECIFIC NEWS

$$\varepsilon_{i,t} | \psi_{i,t} \sim N(0, h_{i,t})$$

$$h_{i,t} = \omega_i + \sum_{j=1}^{i-1} \alpha_{ij} \varepsilon_{j,t}^2 + \sum_{j=i}^{4} \alpha_{ij} \varepsilon_{j,t-1}^2 + \beta_{ii} h_{i,t-1}$$

where $j = 1, 2, 3$, and 4 imply *PACIF*, *TOKYO*, *EUROP*, and *NYORK*, respectively.

Market LHS Variable	Pacific *PACIF*	Tokyo *TOKYO*	Europe *EUROP*	New York *NYORK*
Constant	0.0091[a]	0.0032	0.0168	0.0011
	(0.0031)	(0.0023)	(0.0093)	(0.0010)
$h_{i,t-1}$	0.4258[a]	0.8654[a]	0.5894[a]	0.8891[a]
	(0.1078)	(0.0772)	(0.1744)	(0.0403)
EUROPV(*t*)				−0.0068
				(0.0174)
TOKYOV(*t*)			0.1109[a]	0.0693[b]
			(0.0324)	(0.0269)
PACIFV(*t*)		0.0313	0.0068	0.0583[b]
		(0.0252)	(0.0368)	(0.0291)
NYORKV(*t* − 1)	0.1041[b]	0.0249	0.0694	−0.0175
	(0.0467)	(0.0233)	(0.0379)	(0.0265)
EUROPV(*t* − 1)	0.1558[a]	0.0297	−0.0044	
	(0.0378)	(0.0233)	(0.0404)	
TOKYOV(*t* − 1)	0.2624	−0.0109		
	(0.1398)	(0.0292)		
PACIFV(*t* − 1)	0.0741			
	(0.0472)			
L	−26.3977	−4.8870	−13.8319	−13.4509
Wald(3)[c]	22.5683[a]	2.8820	10.6316[b]	10.2476[b]

[a] Indicates significance at a 1% level.
[b] Indicates significance at a 5% level.
[c] Wald test for the null of heat waves $\alpha_{ij} = 0$, for $j \neq i$: $\sim \chi^2(3)$.
DEFINITIONS: $EUROP(t) = (NYO(t) - TKC(t))/SQRT(7)$; $PACIF(t) = (TKO(t) - NYC(t-1))/SQRT(3)$.

$\alpha_{ij} = 0$, for $j \neq i$ in equation (1). The estimation and test statistics are shown in Table III. Since we do not report the results for heat wave models in the European and Pacific markets, Wald tests are presented for all markets.

These tests check the adequacy of the null hypothesis of heat waves; the significant statistics (except in the Tokyo market) reported in Table III confirm the previous findings that the spillover effects play an essential role in the determinants of intra-daily volatility in the foreign exchange markets.

Next, by examining the estimated coefficients of a column in Table III, we can compare the impacts of news on the per-hour volatility of one market according to its source market. It turns out that the Japanese (Tokyo) news has the largest coefficient for all but the Tokyo markets. This may suggest that the Tokyo news has a greater impact on the volatility spillovers. Markets may take time to interpret the content of news because of diverse private information about fundamentals.

4.4. *Meteor Showers with World-Wide News*

In the above discussions, much attention is paid to the impact of the country-specific news on the exchange rate volatility. In contrast, the market may behave as if there is continuous trading and news over the 24 hour period. In this case the news is effectively a meteor shower and the volatility of the exchange rate should also be a meteor shower. The impact of news on the volatility of the exchange rate would not be subject to terrestrial geography. We call this the world-wide news model and Table IV gives the estimation of such a model.

We stack sequentially all the observations in the Pacific, Tokyo, European, and New York markets to form a world market. Let τ be the index of trading segments and $\varepsilon_{0,\tau}^2$ be the per-hour volatility of the exchange rate change on the τth trading segment.[9] The estimated GARCH(1, 1) model is shown in the first column. In this model, only the news from the nearest trading segment can affect the conditional volatility of exchange rate changes in the current trading segment. The persistence of such news is 0.9667, which is close to those in the heat wave models of Tokyo and New York in Table II. Since the heat wave model presented in Table II and this GARCH(1, 1) meteor shower model are not nested, standard specification tests are not appropriate to this case.

By estimating more general models however, we can compare these specifications. As suggested in the above section, the impact of news on the volatility seems to have a time delay so that the news from the past four trading segments may have an explanatory power on the exchange rate volatility. The likelihood ratio test in the second column supports this viewpoint. After one glance at the coefficients of GARCH(1, 4), we may conclude that most recent news is the most important.

To test whether the news has geographic impacts which differ across markets, we estimate a model nested within the meteor showers model presented in Table III. The result is reported in the third column of Table IV. The null hypothesis is

[9] As shown in the above sections, we denote t as a calendar day. Hence, there are four trading segments in a calendar day t.

TABLE IV

TEST AND ESTIMATION OF METEOR SHOWERS WITH WORLD-WIDE NEWS

$$\varepsilon_{0,\tau} | \psi_{0,\tau} \sim N(0, h_{0,\tau})$$

$$h_{0,\tau} = \omega_0 + \sum_{j=1}^{4} \alpha_{0j} \varepsilon_{0,\tau-j}^2 + \beta_{01} h_{0,\tau-1} + \beta_{04} h_{0,\tau-4}$$

where $\{\varepsilon_{0,\tau}\}_{\tau=1}^{964}$ is a vector stacking *PACIF*, *TOKYO*, *EUROP*, and *NYORK* sequentially; τ is a trading segment index, i.e., $\tau = 4t + i - 1$ for $i = 1, 2, 3$, and 4, implying *PACIF*, *TOKYO*, *EUROP*, and *NYORK*, respectively.

Model	GARCH(1,1)	GARCH(1,4)	GARCH(4,4)
Constant	0.0034[a]	0.0006[a]	0.0119[a]
	(0.0007)	(0.0002)	(0.0023)
$h_{0,\tau-1}$	0.8688[a]	0.9581[a]	
	(0.0201)	(0.0087)	
$h_{0,\tau-4}$			0.5650[a]
			(0.0455)
$\varepsilon_{0,\tau-1}$	0.0880[a]	0.1169[a]	0.0604[a]
	(0.0138)	(0.0204)	(0.0118)
$\varepsilon_{0,\tau-2}$		−0.0627[b]	0.0635[a]
		(0.0292)	(0.0156)
$\varepsilon_{0,\tau-3}$		−0.0047	0.1313[a]
		(0.0292)	(0.0262)
$\varepsilon_{0,\tau-4}$		−0.0181	0.0224
		(0.0103)	(0.0164)
L	−73.0609	−67.4220	−75.2550
LR		11.2778[b,c]	33.3750[b,d]

[a] Indicates significance at a 1% level.
[b] Indicates significance at a 5% level.
[c] Likelihood ratio test for the null of GARCH(1,1) against GARCH(1,4), i.e. $\alpha_{0j} = 0$, for $j = 2, 3$, and 4: $\sim \chi^2(3)$.
[d] Likelihood ratio test for the null of meteor showers with world-wide news against meteor showers with country-specific news. That is, H_0: $\omega_i = \omega_0$, $\alpha_{ii} = \alpha_{04}$, $\beta_{ii} = \beta_{04}$, for $i = 1, \ldots, 4$, and $\alpha_{14} = \alpha_{21} = \alpha_{32} = \alpha_{43} = \alpha_{01}$, $\alpha_{13} = \alpha_{24} = \alpha_{31} = \alpha_{42} = \alpha_{02}$, $\alpha_{12} = \alpha_{23} = \alpha_{34} = \alpha_{41} = \alpha_{03}$: $\sim \chi^2(18)$.

set to be meteor showers with world-wide news, while the alternative is meteor showers with country-specific news. The sum of the likelihood value in Table III is -58.5675 and its corresponding likelihood ratio test is 33.3750, indicating significance at a 5% level with degrees of freedom equal to 18. This result suggests that news is country-specific.

Hence, we conclude that the final meteor showers model of Table III provides the best representation of the data.

5. IMPULSE RESPONSES IN VOLATILITY

Although Table III is suggestive about how a shock in one market influences the future per-hour volatility in the markets around the world, the table does not give us the precise answer. Suppose there is a large shock in New York. Then, the impact of the New York disturbance will influence the per-hour Tokyo volatility through a direct effect in the Tokyo equation and an indirect effect through the increased per-hour volatility in the Pacific market. In order to calculate the impact of the increased per-hour volatility in market j on date t on market i on

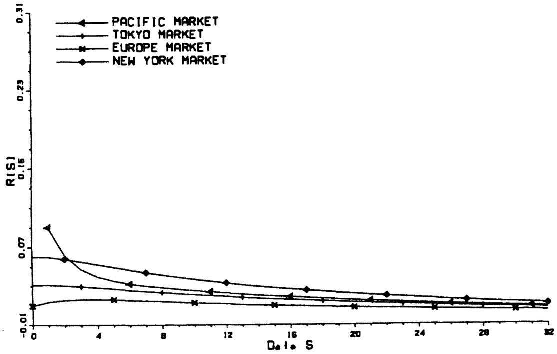

FIGURE 1.—Response to Pacific news.

date $t+k$, the system of four recursive equations, represented in equation (9), has to be solved. This process is analogous to solving the vector autoregressions (VAR) model into moving average representation, and shows the impulse response functions. (See Sims (1980) for the usual definition of impulse response function.)

Figures 1–4 show such impulse responses in per-hour volatility. Given the per-hour shock in one particular market, how per-hour volatilities in other markets will be affected is plotted in each graph. The impact responses can be obtained by solving equation (9). The vertical axis represents the deviation (volatility increment) from the benchmark case, while the horizontal axis represents the days elapsed from the day of the shock.

At a first glance, the impulse response curves exhibit a short run dynamic effect, and then die out approximately after two weeks. In general, the Tokyo per hour news has the largest impact on the per hour predicted conditional variances in all markets. It also responds relatively little to shocks from other markets. Table I reveals that the Tokyo market is the quietest in terms of unconditional variance; apparently whenever there is news, it has important consequences.

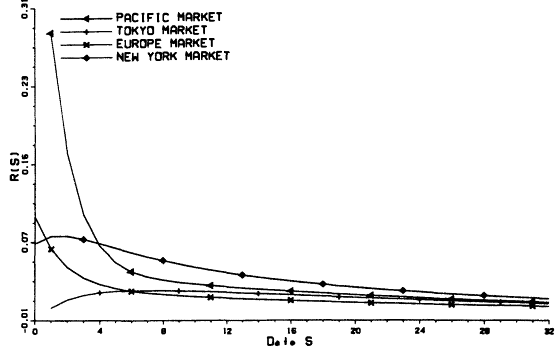

FIGURE 2.—Response to Tokyo news.

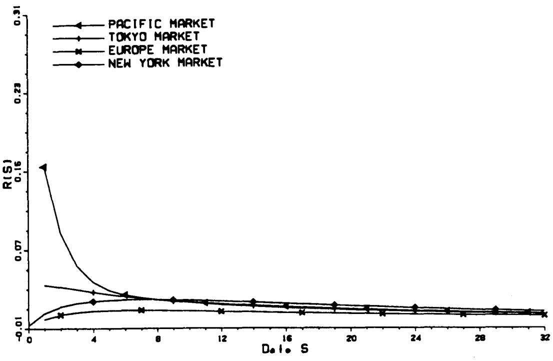

FIGURE 3.—Response to Europe news.

During the one-year period after the Group of Five meeting of September 1985, the coordination between the central banks in the five countries had undergone a change. From September to December 1985, the central banks of the five countries coordinated the depreciation of the dollar, although the amount of intervention and the degree of change in the interest rate constantly surprised the market. In 1986, there were growing signs of conflicts between the U.S. and Japan. The Japanese government was more reluctant to help depreciation of the dollar. In fact the Bank of Japan started to intervene in the market in support of the dollar in March 1986. There were uncertainties about what the Bank of Japan could do to prevent the yen appreciation. (See Ito (1987) for detail of such policy switches.) Our results show that the volatility in the Tokyo market, presumably created by the Bank of Japan policy revelation, had a great impact on the world volatility. It might have been the case that it took several hours or days to precisely interpret the meaning of policy action in Japan.

The eigenvalues of this system are 0.4877, 0.5725, 0.8228, 0.9481, which are an indication of the stationary process. It also confirms that any innovation from

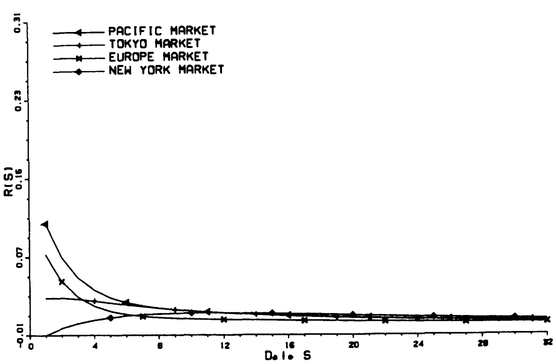

FIGURE 4.—Response to New York news.

one particular market will not persist in the long run. However, this does not prevent a significant interaction of volatility spillovers in the short run.

6. ROBUSTNESS CHECKS

The specification tests in the preceding section support the idea that the volatilities are correlated across intra-daily foreign exchange markets. In this section, additional robustness tests of related hypotheses are performed.

One popular hypothesis in empirical studies is weak-form market efficiency, which implies that past foreign and domestic news or announcements cannot affect the conditional mean of exchange rate movements. This hypothesis has been widely examined in the literature; for example, see Edwards (1982, 1983), Frenkel (1981), and Ito and Roley (1987). The first set of tests checks whether the previous country-specific innovation (in level) has explanatory powers on the mean equation of intra-daily exchange rate changes or not. Since most of those tests reported in the first four rows of Table IV are not significant at the 5% level, the data reveal the robustness of the model specification to this competing hypothesis.

A substantial body of studies from the forward exchange market as well as the other financial markets addresses the evidence that the time varying risk premium for risky assets held by risk averse investors is related to the conditional variance.[10] If we take this view, then intra-daily exchange rate changes may be caused by the time varying conditional variance. If this is the case, then the coefficient of h_t will be significant in the mean return equation. The empirical results reported in Table IV indicate the absence of the volatility effect on intra-daily exchange rate changes in the New York, Tokyo, and Pacific markets, whereas this effect appears in the European market.

The third group of robustness tests investigates holiday and Monday effects on the conditional mean as well as on the conditional variance of the intra-daily exchange rate movements. On the one hand, holiday and Monday effects reveal no significantly explanatory powers in the conditional mean. This is contrary to the findings of French (1980) and Gibbons and Hess (1981) that the Monday effect yields negative returns in the stock market. On the other hand, the Tokyo market shows a significant Monday effect in the conditional variance equation since it is the first organized market open on Monday.

Finally, we check the higher order of the ARCH term and the holiday effect on the sensitivity of ARCH(1) to the conditional variance equation. The results show no evidence of the ARCH(2) effect, i.e. ε_{t-2}^2. The squared lagged innovations after a holiday may be less informative than usual. From this viewpoint, the

[10] For the capital market, see Engle, Lilien, and Robins (1987), Bollerslev, Engle, and Wooldridge (1988). For the foreign exchange market, see Frankel (1982), Hodrick and Srivastava (1984), and Domowitz and Hakkio (1985).

TABLE V

ROBUSTNESS TESTS

Market LHS	Tokyo *TOKYO*	Europe *EUROP*	New York *NYORK*	Pacific *PACIF*	Tokyo *TOKYOV*	Europe *EUROPV*	New York *NYORKV*	Pacific *PACIFV*
TOKYO	2.1048	1.3256	1.4913	9.8501[a]				
EUROP	0.8109	1.8443	0.2786	1.1920				
NYORK	2.3862	0.2984	2.0012	1.8846				
PACIF	3.0979	0.2441	0.7952	0.0836				
h_t	0.3786	7.0034[a]	1.3670	2.4836				
HOLIDAY	0.0621	1.8893	0.0839	1.1116	3.8059	0.4710	3.7703	0.0565
MONDAY	0.0689	0.5055	1.8481	1.0356	6.7716[a]	1.3538	0.6185	2.1960
ARCH(2)					2.9276	0.9460	1.8981	1.7240
$\varepsilon_{t-1}^2 *$ *HOLIDAY*					4.7558[b]	4.0721[a]	0.0595	1.4791

[a] Indicates significance at a 1% level.
[b] Indicates significance at a 5% level.
[c] Lagrangean multiplier test: $\sim \chi^2(1)$.

coefficient in the interaction between $\varepsilon_{i,t-1}^2$ and the holiday dummy could be negative; the data show a significant interaction effect on the conditional variance for the Tokyo and European markets.

7. CONCLUSIONS

Unlike much work on the examination of the efficiency in the foreign exchange market, this paper sheds some light on the cause of volatility clustering of exchange rates. Hence, we propose to examine two types of volatility process—heat waves and meteor showers—for the yen/dollar exchange rates. Using the GARCH model to specify the heteroskedasticity of the intra-daily exchange rate, we find that the empirical evidence is generally against the heat wave hypothesis. This rejection is consistent either with market dynamics which exhibit volatility persistence possibly due to private information or heterogeneous beliefs, or with stochastic policy coordination or competition.

We also investigate the dynamic effect of country specific news on the conditional volatility in the subsequent markets from three angles. First, as shown in Section 4.3, Tokyo (Japanese) news has the largest impact on the volatility spillovers of the yen/dollar exchange rate. This may be due to the existence of private information so that markets take time to interpret the meaning of policy action in Japan. Next, we test whether the news process can be ignorant of terrestrial geography. The hypothesis test also rejects this phenomenon. Third, the impulse response curves are computed to examine the impact of news in one market on the time path of volatility in the other markets. These show a cross-market dynamic effect in the short run which gradually dies out.

Finally, some robustness tests are provided for assessing the validity of the model specifications. Under some circumstances, information about holiday and

Monday dummies may help explain the heteroskedasticity. Generally, the exchange rate process cannot be distinguished from a martingale.

This paper finds a case for volatility clustering of meteor shower type as opposed to the heat wave type. It is left for future research whether it is caused by correlated fundamental news or a failure of strong form market efficiency.

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APPENDIX: DATA SOURCE

The data used in the paper are defined as follows:

$TKO(t)$: the opening (9 AM) yen/dollar in Tokyo on date t.

$TKC(t)$: the closing (3:30 PM) yen/dollar in Tokyo on date t.

$NYO(t)$: the opening (9 AM) yen/dollar in New York on date t.

$NYC(t)$: the closing (4:30 PM, or later if market is active) yen/dollar in New York on date t.

The data in Tokyo are collected daily from *Nihon Keizai Shinbun*, which are the transaction rates. The New York rates are the simple average of bid and ask rates given by the Federal Reserve Bank of New York.

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