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HETEROSKEDASTIC INTRA-DAILY VOLATILITY IN THE FOREIGN EXCHANGE MARKET

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ABSTRACT

This paper defines and tests a form of market efficiency called market dexterity which requires that asset prices adjust instantaneously and completely in response to new information. Examining the behavior of the yen/dollar exchange rate while each of the major markets are open it is possible to test for informational effects from one market to the next. Assuming that news has only country specific autocorrelation such as a heat wave, any intra-daily volatility spillovers (meteor showers) become evidence against market dexterity. ARCH models are employed to model heteroskedasticity across intra-daily market segments. Statistical tests lead to the rejection of the heat wave and therefore the market dexterity hypothesis. Using a volatility type of vector autoregression we examine the impact of news in one market on the time path of volatility in other markets.

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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.[1] This finding is in accord with the efficient market hypothesis as described by Fama(1970). 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.[2] 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 of new information or sluggish information processing by the market. If information comes in clusters, then the market response 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 expectational differences resolved. In either case, the conditional market expectation at every time point could be unbiased, so in that sense it still accords with market effeciency.

We define and propose testing a form of market efficiency called market dexterity. A market is said to be dextrous if the equilibrium price responds instantaneously and completely to news. If there is no news, there will be no price movement in a dextrous market. In particular, old news cannot predict any aspect of the distribution of future asset prices, unless it predicts the change in the arrival process of additional news. Lack of dexterity does not

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[1] For example, Meese and Rogoff (1983a,b) tested the random walk hypothesis against other forecasting formula 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 clock.

[2] 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))

necessarily imply profit opportunities in options or futures markets as these contracts can be priced to reflect the persistence of uncertainty.

In this paper, careful examination of intra-daily exchange rates provides a laboratory where the dexterity hypothesis can be tested. 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. This is a setting where it is unlikely that the news process will be autocorrelated across markets so that volatility spillovers can reasonably be interpreted as evidence against market dexterity.

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. Under market dexterity, the volatility process should also be a heat wave. 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 and therefore we claim evidence against the dexterity of the market.

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 Europe markets. For example, Ito (1987) found that immediately after the Group of Five agreement of September 1985, most of 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 example of country-specific news on the fundamentals.

The meteor shower hypothesis can be interpreted as the lack of dexterity in the market. For example, when the monetary supply statistics are announced in New York at 4:10pm of Thursday, there are less than thirty minutes to trade actively in New York. If all the traders do not share the common belief about the meaning of the announced money supply, then it takes a few hours of actual trading to settle the difference in traders' priors. Ito and Roley (1987) showed the 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 as well as dexterity. 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 the 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 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 market efficiency nor dexterity 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 volatily 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 test the heat wave vs. meteor shower hypotheses. Our statistical tests lead to a rejection of the heat waves hypotheses and hence market dexterity. In section 5, impulse responses of volatility across market segments, that is, an effect of a shock in a market on the volatility of other and own markets in future, 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 non-overlapping markets within a day with market 1 open first. Since major foreign market segments in the world open and close sequentially, the volatilities 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 ϵ_{it} be the intra-daily exchange rate changes in the market i on date t, we can modify the GARCH model as a vector autoregression for volatility:

$$\epsilon_{it} | \psi_{it} \sim N(0, h_{it}) \qquad \text{for } i = 1, 2, \ldots, n \tag{1}$$
$$h_{it} = \omega_i + \beta_{ii} h_{it-1} + \sum_{j=1}^{i-1} \alpha_{ij} \epsilon_{jt}^2 + \sum_{j=i}^{n} \alpha_{ij} \epsilon_{jt-1}^2$$

where ψ_{it} is the information set for market i on date t, which includes the past information on date t-1 and the current information form market 1 to market i-1 on date t, i.e., $\psi_{it} = \{\epsilon_{i-1,t}, \epsilon_{i-2,t}, \ldots, \epsilon_{1t}\} \cup \psi_{nt-1}$, and ψ_{nt-1} denotes the sequence of information sets generated by $\{\epsilon_{1k}, \ldots, \epsilon_{nk}\}_{k=1}^{t-1}$. 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 ϵ_{it} and ϵ_{jt} for $i \neq j$ are uncorrelated follows the first assumption.[3] Third, we set $\epsilon_{jt-1}^2 = 0$ for $j = i+1, \ldots, n$ or $\epsilon_{jt}^2 = 0$ for $j = 1, \ldots, i-1$ if the 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.[4]

The log-likelihood function of equation (1) conditional on the initial values can be expressed as

$$L = T^{-1} \sum_{t=1}^{T} \sum_{i=1}^{n} l_{it} \tag{2}$$

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[3]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.

[4]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 non-trading hours.

$$l_{it} = -1/2 \log h_{it} - 1/2\ (\epsilon_{it}^2 / h_{it})$$

where a constant has been omitted. The estimation and test procedures are simply extended from Engle and Bollerslev . Let $\theta' = (\theta_1', \dots, \theta_n')'$, $\theta_i' = (\omega_i, \beta_{ii}, \alpha_{i1}, \alpha_{i2}, \dots, \alpha_{in})'$, and $w_{it}' = (1, h_{it}, \epsilon_{1t}^2, \dots, \epsilon_{i-1t}^2, \epsilon_{it-1}^2, \dots, \epsilon_{nt-1}^2)'$, and the maximum likelihood estimators (MLE) solve the first order conditions of equation (2):

$$S(\theta_i) = \partial L(\theta_i)/\partial\theta_i = 1/2 \sum_{t=1}^{T} h_{it}^{-1}\ \partial h_{it}/\partial\theta_i\ (\epsilon_{it}^2/h_{it} - 1) \qquad (3)$$

where $\partial h_{it}/\partial\theta_i = w_{it} + \beta_{ii}\ \partial h_{it-1}/\partial\theta_i$. 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 $E(S(\theta)'S(\theta)/T)$. Since the information matrix is block diagonal with respect to θ_i, the single equation estimation of the GARCH model can be performed on each market to yield consistent and efficient estimates. Under suitable regularity and moment conditions, it can be shown that [5]

$$(S(\theta_i)'S(\theta_i))^{1/2} \sqrt{T}\ (\hat{\theta}_i - \theta_i) \sim \mathcal{N}(0, I) \qquad (4)$$

The Lagrangean Multiplier test for the more general model can be constructed by evaluating the score and its information matrix under the null hypothesis:

$$\xi_i = \iota' S_i^o (S_i^{o\prime} S_i^o)^{-1} S_i^o \iota = TR_{io}^2 \qquad (5)$$

where R_{io}^2 is the uncentered R^2 achieved by regressing the unit vector ι on the matrix of scores under the null S_i^o. This statistic is distributed under the null hypothesis as an asymptotic chi-square with the number of degrees of freedom of the restriction .

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 $\alpha_{ij} = 0$

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[5] 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.

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 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 equation can be solved jointly, let $\underset{\sim}{h}_t = (h_{1t},\ldots h_{nt})'$ represent the vector of conditional heteroskedasticities of all the markets on the same date t, and let $\underset{\sim}{\eta}_t = (\epsilon^2_{1t}, \ldots, \epsilon^2_{nt})'$ be the vector of squared innovations or news on this date. Then equation (1) can be written as of date t+1 as

$$\underset{\sim}{h}_{t+1} = \underset{\sim}{\omega} + B\,\underset{\sim}{h}_t + A\,\underset{\sim}{\eta}_{t+1} + C\,\underset{\sim}{\eta}_t \tag{6}$$

where ω is a vector of intercepts, and

$$A = \begin{bmatrix} 0 & 0 & 0 \ldots 0 \\ \alpha_{21} & 0 & 0 \ldots 0 \\ \vdots & & \vdots \\ \alpha_{n1} & \alpha_{n2} & \ldots 0 \end{bmatrix}, \; B = \begin{bmatrix} \beta_{11} & 0 & 0 \ldots 0 \\ 0 & \beta_{22} & 0 \ldots 0 \\ \vdots & & \vdots \\ 0 & 0 & \ldots \beta_{nn} \end{bmatrix}, \; C = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ 0 & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & & & \vdots \\ 0 & \ldots\ldots & & \alpha_{nn} \end{bmatrix}$$

Letting $\underset{\sim}{h}_{t+s/nt} \equiv E(\underset{\sim}{h}_{t+s}|\psi_{nt})$ and taking the iterated expectation $E(E(\epsilon_{it+1}|\psi_{it+1})|\psi_{nt}) = E(h_{it+1}|\psi_{nt})$, this becomes

$$\underset{\sim}{h}_{t+1/nt} = \underset{\sim}{\omega} + B\,\underset{\sim}{h}_t + A\,\underset{\sim}{h}_{t+1/nt} + C\,\underset{\sim}{\eta}_t \tag{7}$$

and for general s step ahead predictions

$$(I - A)\,\underset{\sim}{h}_{t+s/nt} = \underset{\sim}{\omega} + (B + C)\,\underset{\sim}{h}_{t+s-1/nt} \tag{8}$$

Since $\psi_{kt} \subset \psi_{nt}$ for $k = 1, 2, \ldots, n$, by the similar arguments, we can rewrite equation (8) as the more general form:

$$(I - A)\,\underset{\sim}{h}_{t+s/kt} = \underset{\sim}{\omega} + (B + C)\,\underset{\sim}{h}_{t+s-1/kt} \tag{9}$$

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

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

which therefore is

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

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.

$\prod_{i=1}^{n} (\alpha_{ii}+\beta_{ii})$, be less than 1.

Letting $R_{ik}(s)$ be defined as the impulse response of the volatility of the ith market to the squared innovation of the kth market, which is

$$R_{ik}(s) \equiv \partial h_{it+s|kt} / \partial \epsilon_{kt}^2 \quad i,k=1,2,\ldots,n \text{ and } s \in N \cup \{0\}$$

Taking derivatives of equation (9), we can obtain $R_{ik}(s)$ by recursive solution of the following form

$$(I - A)\, \underset{\sim}{R}_k(s) = (B + C)\, \underset{\sim}{R}_k(s-1) \qquad (10)$$

if $s \geq 2$. If the process is stationary, then $\lim_{s\to\infty} \underset{\sim}{R}_k(s) = 0$. By the means of computer simulation, we can easily trace out the impact of the volatility in one market on the time path of 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 will 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 G5 meeting in New York. In this period, as analyzed in Ito (1987), the economic and political news play an important role in the determinants of the exchange rate dynamics. Ito (1987) only identifies the different waves of exchange rate fluctuations by looking at the major news in the respective markets without analyzing the effect of the country-specific news on the volatility of the intra-daily exchange rate changes. However, we still have little solid evidence on how the fundamental news induces the volatility in the respective markets and how well the market adjusts to the new information. Thus, the disaggregation of the market segments is a primary step in understanding the role of news in the determinants of 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 are the main causes of the TOKYO change. Although there is little trading between the close in New York 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 London market and the early morning hours of New York market, the NEW YORK segment mainly reflects the relevant news originating in the U.S. Finally, we define the Europe market, "EUROPE", as the interval between the Tokyo close and New York open.[6]

Table 1 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 Pacific market) are lower in the later period. The per-hour volatility is approximately 0.0860, 0.0647, 0.0663, 0.0766 in the Pacific, Tokyo, Europe, and New York markets implying that Tokyo and Europe are the least volatile markets per hour. Next, the kurtosis in four markets are significantly greater than zero, indicating a fat-tailed distribution. The skewness statistics are not significant from zero except in the Tokyo market, revealing the 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 Europe 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 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 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 2 respectively. Most of the estimated coefficients are significant at a 5% level and then 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 twenty-four hour innovation in

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

Tokyo market has the larger impact on the conditional volatility in the future. They are similar to results in Diebold and Nerlove(1986) and McCurdy and Morgan(1988). In general, the volatility of the daily change in the yen/dollar exchange rate is serially correlated and that there is a 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 todays volatility, but it is not clear whether this is due to daily serial correlation in the country-specific news or volatility spillovers between different market within a day.

4. ESTIMATIONS AND TESTS OF METEOR SHOWER VS HEAT WAVE

4.1 HEAT WAVES

In the following subsection, our attention is focused first on the heat wave model of 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 2. 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 squared change between the opening and closing quotes is a reflection of the domestic volatiltity. The 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 Lagrangean Multiplier test described in Section 2. The results shown in Table 2 indicate that the null hypothesis of heat waves can be rejected at least at the 5% significance level in both the Tokyo and New York markets.

Table 2 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 dexterity in the market, 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 $\alpha_{ij} = 0$, for $j \neq i$ in equation (1). The estimation and test statistics are shown in Table 3. Since we do not report the results for heat wave models in the Europe 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 Tokyo market) reported in Table 3 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 in Table 3, we see that the impacts of news on the volatility of the New York market are -0.00738, 0.07999, 0.14582 and -0.01750 according to the source markets. By the absolute value of those estimated impacts, the relation exhibits an inverse U curve. The same ideas can be applied to the other market segments. The Pacific market also appears an inverse U shape curve whereas the Europe and Tokyo markets exhibit a two-peak curve. In these instances, the fact that the value and the timing of information are not negatively related may be attributable to the characteristics of how fast the news could be digested in the market. We may infer from the pattern of the inverse U shape curve that the market lacks dexterity in handling the information.

5. IMPULSE RESPONSES IN VOLATILITY

Although table 3 is suggestive about how a shock in one market influences the future 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 Tokyo volatility through a direct effect in the Tokyo equation and an indirect effect through the increased volatility in the Pacific market. In order to calculate the impact of the increased volatility in market j on date t on the market i on date $t+k$, the system of four recursive equations, represented in equation (10), 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)).

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 reponses can be obtained by solving equation (10) and multiplying by the realtive business hour ratio of the source market to the respondent market. 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 1 reveals that the Tokyo market is the quietest in terms of unconditional variance; apparently whenever there is news, it has important consequences.

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 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 foreign exchange market is not dextrous in that the volatilities are correlated across intra-daily markets. In this section, additional robustness tests of related hypotheses are performed.

One of popular hypotheses in the empirical studies is the weak-form market effeciency, which implies that the 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 check 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 4 (except in the Pacific market) 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 address the evidence that the time varying risk premium for risky assests held by risk averse investors is related to the conditional variance.[7] 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

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

equation. The empirical results reported in Table 4 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 Europe market.

The third group of robustness tests investigate 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 Gibbon 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 in 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^2_{t-2}. In case of the preceding holidays, the squared lagged innovations from the same market actually arising from the previous two or three days may not be worth as much as that of the no preceeding holiday case. From this viewpoint, the coefficient in the interation between ϵ^2_{it-1} and the holiday dummy is supposed to be negative, and the data show a rejection of the interaction effect on the conditional variance for the Tokyo and Europe markets

7. CONCLUSIONS

Unlike much work on the examination of the efficiency in the foreign exchange market, this paper sheds some light on volatility clustering of the exchange rate. We propose and test the concept of dexterity. In particular, the GARCH model is employed to determine the sources causing the intra-daily volatility in the disaggregated market segments with the data of the yen/dollar exchange rate from October 3, 1985 to September 26, 1986. Two competing hypotheses - heat waves and meteor showers - are proposed to examine the dexterity of the yen/dollar exchange market. The empirical results are generally against the heat waves hypothesis, implying either that the yen/dollar foreign exchange market is not dextrous and suffers from volatility spillovers or that volatility clusters because of stochastic policy coordination. However, the role of market dexterity in Tokyo is not conclusive since it is not robust to the disaggregation of market segments. To understand the value of information, we then investigate the extent to which market-specific news affects the conditional variances in the subsequent markets.

The empirical evidences yield conclusions in the above two principal issues. First, the timing and the impact of the arrival of information do not exhibit a negative correlation. Usually, there exists an inverse U curve or two peak curve, indicating either a time lag in response to the news or a different value of the news to the traders. Second, in the reactions to the various innovations, the impulse response curves show a cross-market dynamic effect in the short run and then die out. Judging from eigenvalues with modulus being less than one, we may conclude that the volatility process of the intra-daily exchange rate dynamics is approximately stationary.

Finally, some robustness tests are provided for supporting the validity of the model specifications. Under some circumstances, information about holiday and Monday dummies may help explain the heteroskedasticity. In the Tokyo and New York markets, the exchange rate process cannot be distinguished from a martingale. According to this finding, the market efficiency in the mean is supported but not market dexterity.

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.

TABLE 1 DATA SUMMARY

MARKET VARIABLE	TOKYO TOKYO	EUROPE EUROP	NEW YORK NYORK	PACIFIC PACIF
MEAN	-0.02094 (0.61341)	-0.10659 (0.01625)	-0.05334 (0.26865)	-0.05894 (0.07471)
VARIANCE	0.42084	0.46425	0.57432	0.25811
SKEWNESS[b]	-0.77302 (0.00000)	-0.25301 (0.11475)	-0.18253 (0.24442)	0.04382 (0.78480)
KURTOSIS[b]	3.37254 (0.00000)	2.95699 (0.00000)	1.81818 (0.00000)	2.52750 (0.00000)
Q(12)[c]	10.64547 (0.55952)	7.79972 (0.80058)	14.60735 (0.26361)	11.53920 (0.48336)
Q(24)[c]	17.95751 (0.80506)	22.16280 (0.56955)	37.60394 (0.03805)	21.45775 (0.61160)
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) Q(12) and Q(24) denote the Box-Periece tests for up to 12th and 24th serial correlations respectively.

<u>Definitions</u>:

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)

TABLE 2 ESTIMATIONS AND TESTS OF DAILY, HEAT WAVE AND FOREIGN METEOR SHOWER MODELS

$$\epsilon_{it} \mid \psi_{it} \sim N(0, h_{it})$$

$$h_{it} = \omega_i + \alpha_{ii}\,\epsilon^2_{it-1} + \beta_{ii}\,h_{it-1} + \gamma_i\,\eta^2_{it-1}$$

where ϵ_{it} is the close-close change of the ith market in daily model or the open-to-close change of the ith market in heat wave or foreign meteor shower models. η_{it-1} is the change from the close on day t-1 to the open on day t.

MARKET LHS VARIABLE	TOKYO TK24	TOKYO TOKYO	TOKYO TOKYO	NEW YORK NY24	NEW YORK NYORK	NEW YORK NYORK
CONSTANT	0.14758[b] (0.06465)	0.01938 (0.01250)	-0.01060[a] (0.00380)	0.06133 (0.35202)	0.02512 (0.01693)	-0.01358[a] (0.00354)
ϵ^2_{it-1}	0.21773[a] (0.05614)	0.04119[b] (0.02031)	-0.05145[a] (0.00773)	0.00614 (0.02138)	0.08093[a] (0.03217)	-0.00966 (0.00950)
h_{it-1}	0.71844[a] (0.06328)	0.91154[a] (0.04856)	0.96752[a] (0.01066)	0.95952[a] (0.21450)	0.87514[a] (0.04400)	0.98617[a] (0.00819)
η^2_{it-1}			0.02821[a] (0.00397)			0.01965[a] (0.00301)
L	-413.3072	-236.8152	-228.1822	-424.6929	-276.8411	-263.5462
LM(1)[c]			5.3477[b]			10.7486[a]

(a) significant at a 1% level.

(b) signifiacnt at a 5% level.

(c) Lagrangean Multipilier 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).

NY24(t) = NYC(t) - NYC(t-1).

$\eta_{TOKYO}(t-1)$ = TKO(t)-TKC(t-1)

$\eta_{NYORK}(t-1)$ = NYO(t)-NYC(t-1)

TABLE 3 TEST AND ESTIMATION OF METEOR SHOWERS WITH COUNTRY-SPECIFIC NEWS

$$\epsilon_{it} \mid \psi_{it} \sim N(0, h_{it})$$

$$h_{it} = \omega_i + \sum_{j=1}^{i-1} \alpha_{ij} \epsilon_{jt-1}^2 + \sum_{j=i}^{4} \alpha_{ij} \epsilon_{jt}^2 + \beta_{ii} h_{it-1}$$

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

MARKET LHS Variable	PACIFIC PACIF	TOKYO TOKYO	EUROPE EUROP	NEW YORK NYORK
CONSTANT	0.02738[a] (0.00923)	0.02084 (0.01505)	0.11752 (0.06478)	0.00862 (0.00766)
h_{it-1}	0.42578[a] (0.10781)	0.86543[a] (0.07721)	0.58938[a] (0.17438)	0.88906[a] (0.04027)
EUROPV(t)				-0.00738 (0.01865)
TOKYOV(t)			0.10349[a] (0.03491)	0.07999[b] (0.03101)
PACIFV(t)		0.06785 (0.05461)	0.01579 (0.08578)	0.14582[b] (0.07271)
NYORKV(t-1)	0.04163[b] (0.01865)	0.02157 (0.02015)	0.06473 (0.03534)	-0.01750 (0.02651)
EUROPV(t-1)	0.06675[a] (0.01620)	0.02762 (0.02779)	-0.00436 (0.04035)	
TOKYOV(t-1)	0.12113 (0.06450)	-0.01086 (0.02924)		
PACIFV(t-1)	0.07407 (0.04720)			
L	-156.0340	-234.1828	-243.4493	-262.2915
WALD(3)[c]	22.5683[a]	2.8820	10.6316[b]	10.2476[b]

(a) significant at a 1% level.

(b) significant at a 5% level.

(c) Wald test for the null of heat waves $\alpha_{ij} = 0$, for $j \neq i$: $\sim \chi^2(3)$.

TABLE 4 ROBUSTNESS TESTS

MARKET	TOKYO	EUROPE	NEW YORK	PACIFIC	TOKYO	EUROPE	NEW YORK	PACIFIC
LHS	TOKYO	EUROP	NYORK	PACIF	TOKYOV	EUROPV	NYORKV	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
ϵ^2_{t-1}*HOLIDAY					4.7558[b]	4.0721[a]	0.0595	1.4791

(a) signifiacnt at a 1% level.

(b) signifiacnt at a 5% level.

(c) Lagrangean Multiplier test : $\sim \chi^2(1)$.

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FIG. 1 RESPONSE TO PACIFIC NEWS

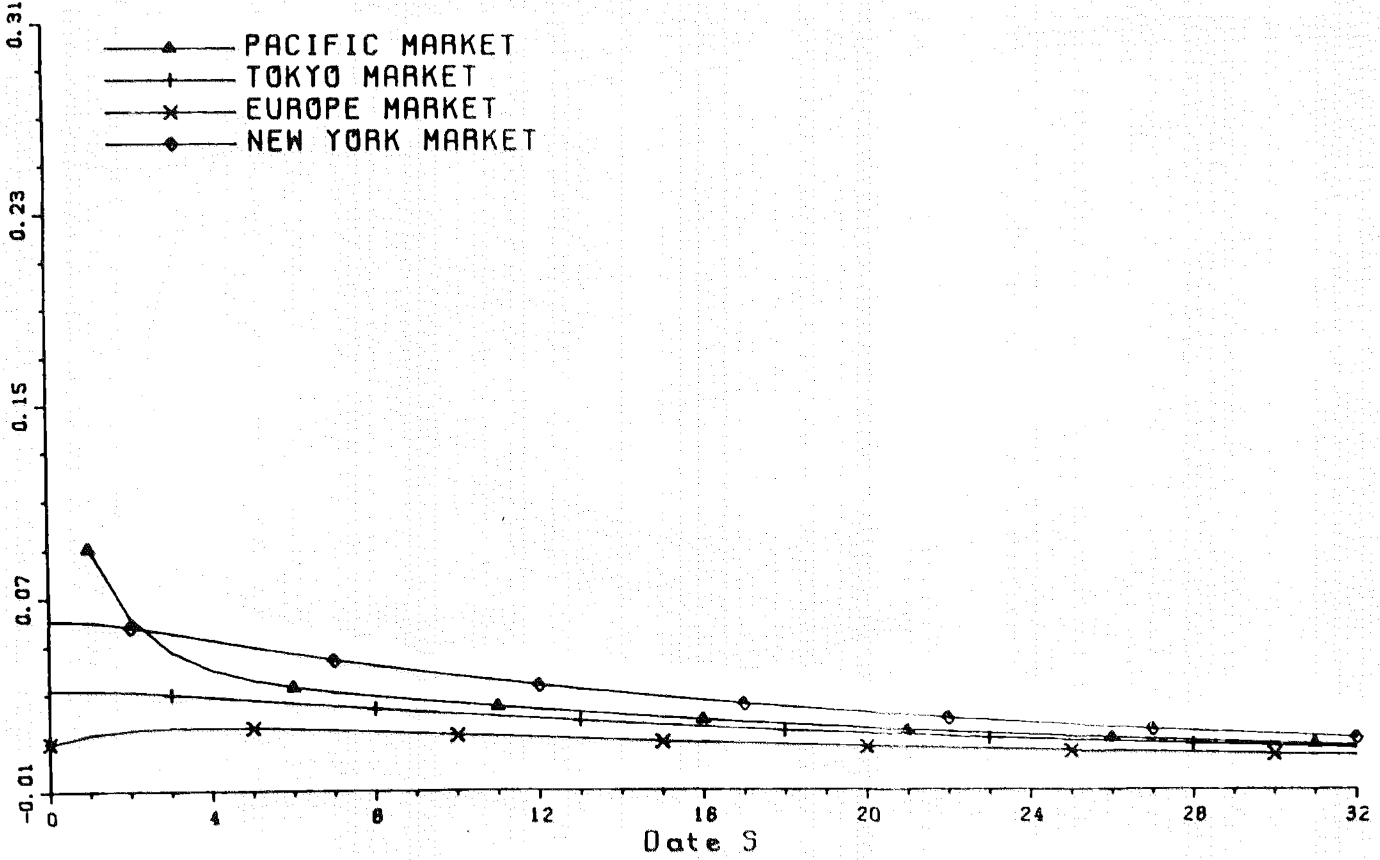

FIG. 2 RESPONSE TO TOKYO NEWS

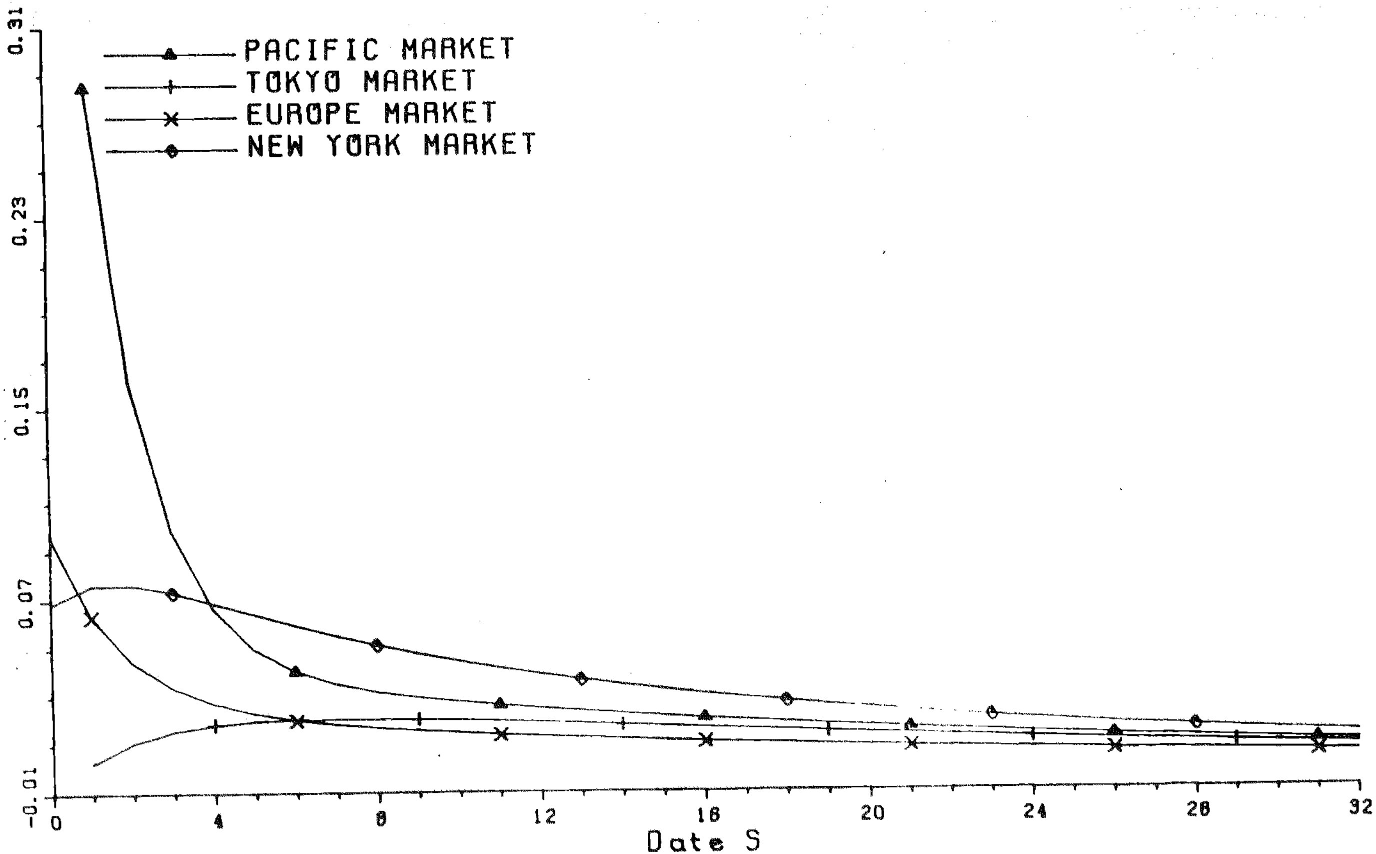

FIG. 3 RESPONSE TO EUROPE NEWS

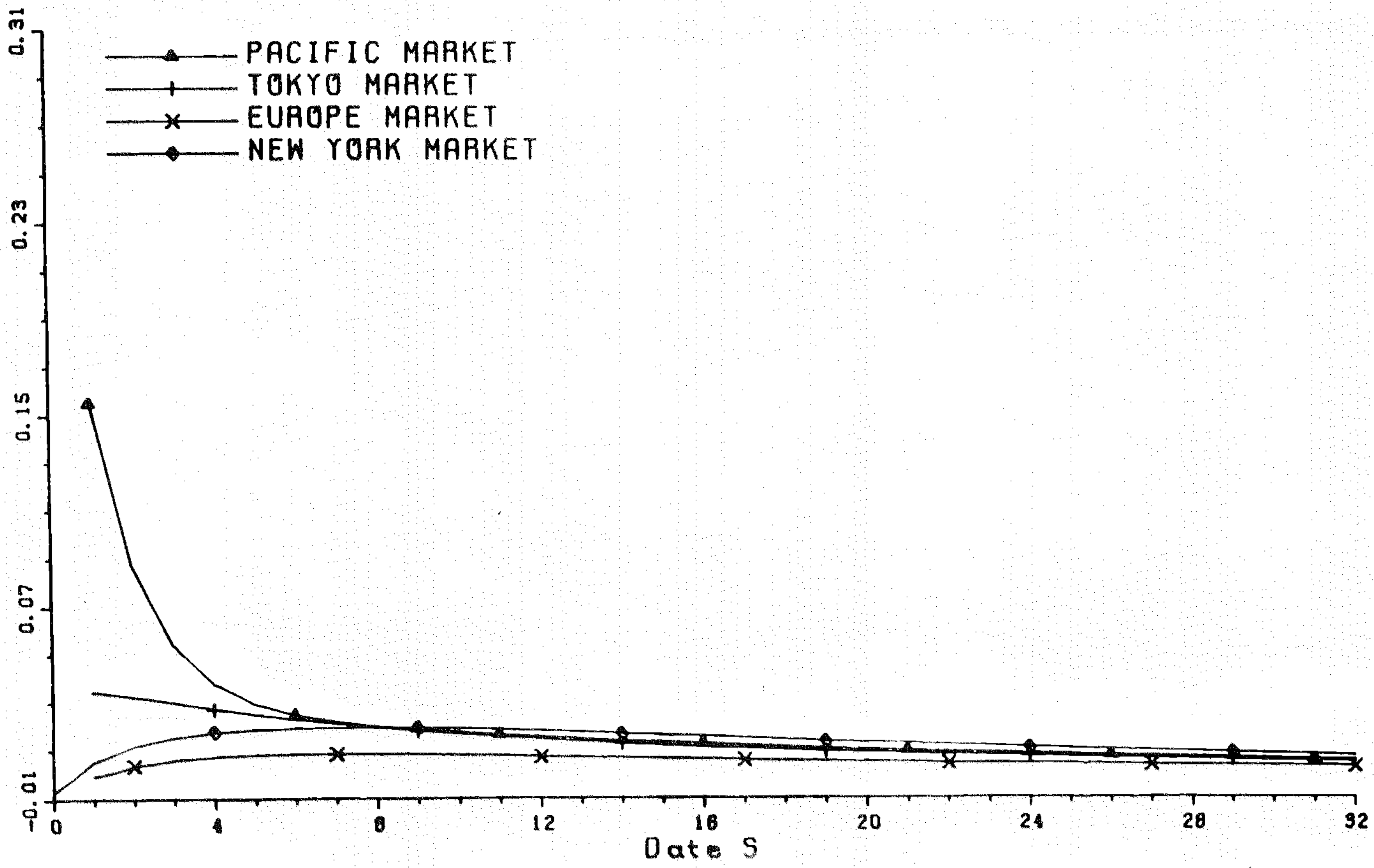

FIG. 4 RESPONSE TO NEW YORK NEWS