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Takatoshi Ito

Robert F. Engle

Wen-Ling Lin

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ABSTRACT

The purpose of this paper is to examine the intra-daily volatility of the yen/dollar exchange rate over three different regimes from 1979 to 1988 which correspond to different degrees of international policy coordination. In each regime we test for heat wave vs. meteor shower effects. The heat wave hypothesis assumes that volatility has only country specific autocorrelations, while the meteor shower hypothesis allows volatility spillovers from one market to the next. Meteor showers can be caused by stochastic policy coordination, by gradual release of private information, or by market failures such as fads, bubbles or bandwagons. The rejection of the heat wave model over the first half of the 1980s discredits the stochastic policy coordination interpretation because there was little policy coordination among industrial countries prior to the Plaza Agreement in 1985.

Wen-Ling Lin
Department of Economics
University of Wisconsin, Madison
1180 Observatory Drive
Madison, WI 53706

Takatoshi Ito
Institute of Economic Research
Hitotsubashi University
Kunitachi, 186 Tokyo
JAPAN

Robert F. Engle
Department of Economics
D-008
University of California
San Diego, CA 92093

1. INTRODUCTION

Because of the nearly contemporaneous collapse of the world stock markets in October 1987 and 1989, the international transmission of intra-daily asset returns or volatility has received considerable attention. See, for example, Engle, Ito, and Lin (1990), and Lin (1989) in the foreign exchange market; King and Wadhwani (1990), Neumark, Tinsley, and Toshini (1988), and Hamao, Masulis, and Ng (1990) in the international stock markets. These studies find that volatility in one market tends to continue after that market closes, producing volatility in markets opening several hours later even though these markets are geographically distant. This phenomenon is dubbed a "meteor shower" by Engle, Ito and Lin (1990) because of its similarity to the pattern of meteor showers as the globe turns. The finding is contrary to the more natural expectation that the volatility would instead continue in the same market the next day, the "heat wave" hypothesis. Meteor showers appear to represent a failure of the market to fully process its information and may signal a violation of market efficiency since it is unlikely that the sources of volatility are so geographically mobile.

While various market failures such as fads, bubbles, bandwagons etc. could be the explanation for the meteor shower finding, there are at least two models of optimizing agents which lead to this type of process. The first is due to the gradual dissemination of private information by rational agents. The analyses of Kyle (1985) and Admati and Pfleiderer (1988) provide rigorous models of this type. Specifically, they model the trading strategy of uninformed liquidity traders and optimizing traders with private information, and show that the private information is only gradually incorporated into prices, with the price at the end of the relevant trading interval finally reflecting all private information.

Therefore, such market dynamics may cause the continuity of volatility after a shock ends.

Second, spillovers can result from stochastic policy coordination among industrial countries. Suppose the volatility in one country is caused by a policy change or announcement, then the following government may stochastically respond, leading to a volatility spillover. For example, if a shift in fiscal policy of the United States increases the uncertainty of the monetary stance of the Bank of Japan, then the volatility of exchange rates in these two markets would appear to be a meteor shower.

Attitudes toward exchange rate policy coordination among the major industrial countries dramatically changed after the Plaza Agreement of September 22, 1985. Examples are a concerted intervention in the foreign exchange market, coordinated discount rate cuts during 1985–1986, and the Louvre accord to set nominal exchange rates to a certain level. (See Ito (1988) and Obstfeld (1988).) These examples of policy coordination among industrial countries after G5 offer a natural experiment as to how important policy coordination is in causing a meteor shower.

Another important event relevant to our research was the enactment of the Japanese Foreign Exchange and Foreign Trade Control Law on December 1, 1980. This law removed all the barriers to capital flows into and out of Japan. If capital controls are in effect, some arbitrage opportunities appear to be left unexploited (e.g., Dooley and Isard (1980) and Ito (1986)). If participants in New York are not allowed to trade in the Japanese market, the revelation of private information from New York may be less in Tokyo. Hence, it can mitigate the meteor shower effect in Tokyo. On the contrary, the removal of capital controls can internationalize the Japanese financial markets so that Tokyo news should play a more important role in promoting exchange rate volatility than before.[1]

Our previous paper shows evidence in favor of meteor showers after the Plaza Agreement. In that paper we cannot distinguish whether such a meteor shower is caused by stochastic policy coordination, or by the behavior of the market itself. This paper extends the previous study in the following three ways.

First, we examine the volatility of the yen/dollar exchange rate during 1979–1988 in order to disentangle the causes of meteor showers. The period after the Japanese deregulation of capital controls and before the Plaza Agreement provides an almost ideal experiment for our study because of little policy coordination among the industrial countries during this period. Therefore, any volatility spillovers in that period can be attributed to the gradual dissemination of private information, or market failures such as fads or bandwagons.

Second, we propose a decomposition of volatility into components due to heat waves and to meteor showers. This allows us to measure the relative importance of these factors.

Third, we test whether the market behaves as if there is continuous trading over twenty-four hours so that the impact of news is not subject to terrestrial geography. We also examine whether a policy regime shift generates a structural change in the volatility process.

Following this introductory section, a simple asset view of exchange rate

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[1]There may be other policy regimes during our sample period such as the shift of the Fed's operation procedures from borrowed reserves to non borrowed reserves. However, we think that capital controls and policy coordination are the most relevant and important to test the heat wave hypothesis.

determination is presented in Section 2 to explain how stochastic policy coordination can cause meteor showers. Section 3 describes the ARCH models used for the analysis. The data summary for the behavior of the yen/dollar exchange rate is reported in Section 4.1. Two breaking points for the whole sample period, corresponding to the Japanese deregulation of capital controls and the Plaza Agreement, are also discussed. In Section 4.2, we estimate the meteor shower model for three policy regimes. We also test the heat wave vs. meteor shower hypotheses for each of three regimes. Using the variance decompositions we compare the relative contributions of news to determining the exchange rate volatility in Section 5.1. In Section 5.2, we test for no geographic impact of news and for the stability of the volatility process of the yen/dollar exchange rate. The final section summarizes the main conclusions of this paper.

2. A THEORETICAL FRAMEWORK

In this section we formulate a simple asset market approach to exchange rate determination as shown in Mussa (1982) and Frenkel (1981) which explains how stochastic policy coordination can cause volatility spillovers. Consider a two-country world with the domestic market open first. Two countries' residents can trade in either one of the two markets once a day. Let asterisk (*) denote the market fundamental variables in the foreign country. Let t be a calendar day, v_t (v_t^*) be the policy variable for the domestic (foreign) country, z_t (z_t^*) be the fundamental variable in the private sector of the domestic (foreign) country, and s_t (s_t^*) be the logarithm of the closing exchange rate of the two countries' currencies in the domestic (foreign) market. An asset view of the exchange rate determination implies that [2]

$$s_t = z_t + v_t + v^*_{t-1} + \alpha\,(E_t\, s^*_t - s_t) \qquad (1)$$

$$s^*_t = z^*_t + v_t + v^*_t + \alpha\,(E^*_t\, s_{t+1} - s^*_t) \qquad (2)$$

where E_t (E^*_t) is an expectation operator conditional on ψ_t (ψ^*_t), and ψ_t (ψ^*_t) is the information set available as the domestic (foreign) market is open. The parameter α is the interest elasticity of the demand for money. Solving the two equations, we can get the exchange rate as the present discounted values of future expected market fundamentals. The solution without bubbles is:

$$s_t = \frac{1}{(1+\alpha)} \sum_{k=0}^{\infty} \cdot \left(\frac{\alpha}{1+\alpha}\right)^{2k} E_t(z_{t+k} + v_{t+k} + v^*_{t+k-1})$$

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[2]Consider the following simple log-linear monetary model with the domestic market open:

Money Demand:

$$M_t - p_t = \lambda\, y_t - \alpha\, i_t$$

$$M^*_{t-1} - p^*_{t-1} = \lambda\, y^*_{t-1} - \alpha\, i^*_{t-1}$$

Purchasing Power Parity:

$$p_t - p^*_{t-1} - s_t = u_t$$

Uncovered Interest Parity:

$$i_t - i^*_{t-1} = E_t\, s^*_t - s_t$$

where M_t is the domestic money stock, p_t is the domestic price level, s_t is the value of domestic currency per unit foreign currency, u_t is a shock deviated from purchasing power parity, and i_t is the domestic interest rate.

The solution to this model is

$$s_t = M_t - M^*_{t-1} - \lambda(y_t - y^*_{t-1}) - u_t + \alpha\,(E_t\, s^*_t - s_t)$$

Thus, $v_t = M_t$, $v^*_{t-1} = -M^*_{t-1}$, and $z_t = -\lambda(y_t - y^*_{t-1}) - u_t$

$$+ \frac{\alpha}{(1+\alpha)^2} \sum_{k=0}^{\infty} \left(\frac{\alpha}{1+\alpha}\right)^{2k} E_t(z^*_{t+k}+v_{t+k}+v^*_{t+k}) \quad (3)$$

$$s^*_t = \frac{1}{(1+\alpha)} \sum_{k=0}^{\infty} \left(\frac{\alpha}{1+\alpha}\right)^{2k} E^*_t(z^*_{t+k} + v_{t+k} + v^*_{t+k})$$

$$+ \frac{\alpha}{(1+\alpha)^2} \sum_{k=0}^{\infty} \left(\frac{\alpha}{1+\alpha}\right)^{2k} E^*_t(z_{t+k+1} + v_{t+k+1} + v^*_{t+k}) \quad (4)$$

We assume that the market fundamental variables follow the following general exogenous processes:

$$z_t = z^*_{t-1} + \epsilon_t \qquad \text{with } \epsilon_t | \psi^*_{t-1} \sim D(0,h_{\epsilon,t}) \quad (5)$$

$$z^*_t = z_t + \epsilon^*_t \qquad \text{with } \epsilon^*_t | \psi_t \sim D(0,h^*_{\epsilon,t}) \quad (6)$$

$$\Delta v_t = \eta_t + \eta^*_{t-1}(\rho + \xi_t) \qquad \text{with } \eta_t | \psi^*_{t-1} \sim D(0,h_{\eta,t}),\ \ \xi_t | \psi^*_{t-1} \sim D(0,\sigma^2) \quad (7)$$

$$\Delta v^*_t = \eta^*_t + \eta_t(\rho^* + \xi^*_t) \qquad \text{with } \eta^*_t | \psi_t \sim D(0,h^*_{\eta,t}),\ \ \xi^*_t | \psi_t \sim D(0,\sigma^{*2}) \quad (8)$$

where η_t, η^*_t, ϵ_t, ϵ^*_t, ξ_t, and ξ^*_t, are contemporaneously and serially uncorrelated for all t and have distributions D with mean zero and variances which may vary over time.[3] The movement of these variances is naturally described as autocorrelated within each market and is therefore a heat wave although we will consider other cases. The innovations, i.e., $\epsilon_t(\epsilon^*_t)$, $\eta_t(\eta^*_t)$, and $\xi_t(\xi^*_t)$, are realized only when the domestic (or foreign) market is open. Thus, we can denote ψ_t as $\{\eta_s,\eta^*_s,\epsilon_s,\epsilon^*_s,\xi_s,\xi^*_s\}_{s=t-1}^{s=-\infty} \cup \{\eta_t,\epsilon_t,\xi_t\}$, and ψ^*_t as $\psi_t \cup \{\eta^*_t,\epsilon^*_t,\xi^*_t\}$. Equations (7) and (8) indicate the reaction functions of these two countries' policy variables. Note that these reaction functions allow for new surprises, predictable reactions to previous policy variables, and stochastic reactions to

[3]In empirical investigation, we assume that D is an normal distribution. The normality assumption will be tested, and the robust standard errors to the density will be provided if such a test fails.

previous policy variables. This variety of types of policy coordination will be discussed in detail below.

According to the exogenous processes (5) - (8), the intra-daily changes in the exchange rate are

$$s_t^* - s_t = \epsilon_t^* + \left(1 + \frac{\alpha\rho}{1+\alpha}\right)\eta_t^* + \frac{\rho^*}{1+\alpha}\eta_t + \eta_t \xi_t^* \qquad (9)$$

$$s_t - s_{t-1}^* = \epsilon_t + \left(1 + \frac{\alpha\rho^*}{1+\alpha}\right)\eta_t + \frac{\rho}{1+\alpha}\eta_{t-1}^* + \eta_{t-1}^* \xi_t \qquad (10)$$

Their variances conditional on the past information set are

$$\mathrm{Var}_t(s_t^* - s_t) = h_{\epsilon,t}^* + \left(1+\frac{\alpha\rho}{1+\alpha}\right)^2 h_{\eta,t}^* + \eta_t^2 \sigma^{*2} \qquad (11)$$

$$\mathrm{Var}_{t-1}^*(s_t - s_{t-1}^*) = h_{\epsilon,t} + \left(1+\frac{\alpha\rho^*}{1+\alpha}\right)^2 h_{\eta,t} + \eta_{t-1}^{*2} \sigma^2 \qquad (12)$$

where Var_t (Var_{t-1}^*) is a variance operator conditional on ψ_t (ψ_{t-1}^*).

These equations provide the main theoretical results on volatility spillovers. A meteor shower requires that information in the other market is useful in predicting this market variance. Equation (11) shows that the volatility of the exchange rate in the foreign market, $\mathrm{Var}_t(s_t^* - s_t)$, depends only on foreign information through $h_{\epsilon,t}^*$ and $h_{\eta,t}^*$ and on domestic information through $\eta_t^2 \sigma^{*2}$. If $\sigma^{*2}=0$ so that $\xi_t^* = 0$ for all t, then the third term of equation (11) disappears and the foreign volatility is a heat wave, not a meteor shower. Thus, only stochastic policy coordination, not deterministic policy coordination, leads to meteor showers.

Several special cases which may cause meteor showers are now discussed.

Case 1: Real Meteor Showers

Real meteor showers can be due to the linkage of real economies through world-wide news. For example, if an increase in the arrival rate of technology shocks in the United States can increase the arrival rate of such shocks in

Japan, then it can induce the meteor shower effect. In this case, we assume the constant variance of all policy variables (e.g., $h_{\eta,t}=h_{\eta}$, and $h^*_{\eta,t}=h^*_{\eta}$), no policy coordination (e.g., $\xi_t=\xi^*_t=0$ for all t, and $\rho=\rho^*=0$), but specify meteor shower processes of private sector shocks (e.g., $h_{\epsilon,t}=bh^*_{\epsilon,t-1}+a\epsilon^{*2}_{t-1}$, and $h^*_{\epsilon,t}=b^*h_{\epsilon,t}+a^*\epsilon^2_t$). Then, the conditional variance of intra-daily exchange rates in equation (11) becomes

$$Var_t(s^*_t - s_t) = b^*h_{\epsilon,t}+a^*\epsilon_t^2 + h^{*2}_{\eta} \tag{13}$$

Since $\epsilon_{t-1} = s_t-s^*_{t-1}+\eta_t$, the conditional variance of $s^*_t - s_t$ depends on the intra-daily changes in exchange rate in the domestic market.

Case 2: Deterministic Policy Coordination ("Deterministic" Reaction Function through ρ)

In the conventional policy coordination, the government reacts to the other countries' policy variables in order to make Pareto-improving gains.[4] (See Hamada (1985).) The reactions of policy are expressed in ρ and ρ^*. The coordinated discount rate cuts among the group of five countries in March and April of 1986 are the examples. Assuming that $h_{\epsilon,t}=h_{\epsilon}$, $h^*_{\epsilon,t}=h^*_{\epsilon}$, and $\xi_t=\xi^*_t=0$ for all t, we can find spillovers in mean.[5]

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[4]Some authors cast doubt on the welfare gains from coordination. Rogoff (1985) showed that the cooperative monetary policy can exacerbate the central banks credibility problems and yield a higher inflation rate. Frankel and Rockett (1988) simulated ten leading econometric models to show that a cooperative policy package international policy makers agree on may not improve welfare if it is not the correct macroeconomic model.

[5]If uncovered interest rate parity holds, then the excess returns on the domestic currency denominated securities are still a martingale. There is no profit

$$E_t(s_t^* - s_t) = \frac{\rho^*}{1+\alpha}\,\eta_t \tag{14}$$

although these are small since α is a large number.

The conditional variance of $s_t^* - s_t$ is

$$\mathrm{var}_t(s_t^* - s_t) = h_\epsilon^{*2} + \left(1 + \frac{\alpha\rho}{1+\alpha}\right)^2 h_{\eta,t}^* \tag{15}$$

Equation (15) implies that if the policy innovation, η_t, follows a heat wave, then the variance of $s_t^* - s_t$ conditional on ψ_t is a heat wave. Since the direction and the magnitude of policy coordination are known, there is no room for the meteor shower effect.

Case 3: Stochastic Policy Coordination

In contrast to the deterministic policy coordination, stochastic policy coordination can cause a meteor shower even if the stochastic processes of η and η^* are a heat wave. In this case, the government reaction to a foreign shock η^* is to set its shock to $(\rho+\xi)\eta^*$. This policy response actually increases the volatility of shocks over the case when there was no foreign policy shock. If the standard deviation of ξ which represents the variance of the policy response, is large, then this effect can be substantial.

When $\rho=\rho^*=0$, policy reactions convey no direction, merely an uncertainty. Under this rule, there is no spillover effect on mean but there is on variance. The conditional variance of the intra-daily exchange rate is

$$\mathrm{Var}_t(s_t^* - s_t) = h_\epsilon^{*2} + h_{\eta,t}^* + \sigma^2\eta_t^2 \tag{16}$$

The example of conflicts between the United States and Japan in 1986 can illustrate such stochastic policy coordination. In fact, the bank of Japan began

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opportunity. Since the intra-daily interest rate differential is very small, the spillover effect becomes tiny.

intervening in the market in support of the dollar in March. There was uncertainty about whether the Fed would support or prevent the depreciation of the dollar.

A simple framework illustrates the importance of stochastic policy coordination. Suppose the domestic government chooses to respond completely with some probability π and not to respond with probability $1-\pi$. Then the parameters in (7) can be interpreted as $\rho=\pi$ and $\xi = \{(1-\pi)$ with probability π, and $= -\pi$ with probability $(1-\pi)\}$. The mean of the response is the deterministic policy while the deviations from this mean are the stochastic response. Hence the variance of ξ is just $\sigma^2=\pi(1-\pi)$ and equation (12) still shows the meteor shower effect. The policy variance is $\eta^{*2}\sigma^2$ which depends also upon the size of the foreign policy shock. Of course, if the foreign country maintains $\sigma^{*2} = 0$, then the meteor shower is only in one direction. This formulation of the problem is very close to the formulation of the Peso problem (see, for example, Obstfeld(1987)).

Although we are unable to identify all the parameters in the structural model, we will test the economic implications of the three special cases.

3. ECONOMETRIC SPECIFICATION

As Mussa (1979) pointed out, 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. While this has been widely observed in daily or less frequent data, Engle, Ito, and Lin (1990) found that the volatility clustering of exchange rates also in intra-daily data. Volatility clusters around the clock instead of geographically over time. Such time series properties can be modeled by (Generalized) Autoregressive Conditional Heteroskedasticity (GARCH) models. Engle and Bollerslev (1986), Domowitz and Hakkio (1985), Diebold and Nerlove (1988), and McCurdy and Morgan (1988) have used the GARCH model to specify such a dynamic process of exchange rate volatility. In this section, we present an extended version of the GARCH model of Engle (1982) and Bollerslev (1986).

We assume that there are four non-overlapping markets (i.e., Pacific, Tokyo, Europe, and New York) within a day with market 1 (i.e., Pacific) open first. Let $\epsilon_{i,t}$ be the intra-daily exchange rate change divided by the square root of business hours in market i on date t.[6] The information set for market i, $\psi_{i,t}$, includes the past information on date t-1 and the current information from market 1 to market i-1 on date t. Let D be an normal distribution, the GARCH model for the per-hour volatility can be specified as the following form:

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

$$h_{i,t} = \omega_i + \beta_{ii} h_{i,t-1} + \sum_{j=1}^{i-1} \alpha_{ij} \epsilon^2_{j,t} + \sum_{j=i}^{4} \alpha_{ij} \epsilon^2_{j,t-1} \tag{17}$$

for i = 1 (Pacific), 2 (Tokyo), 3 (Europe), and 4 (New York).

where $\psi_{i,t} = \{\epsilon_{i-1,t},\epsilon_{i-2,t},\ldots,\epsilon_{1,t}\} \cup \psi_{4,t-1}$, and $\psi_{4,t-1}$ denotes the sequence of information sets generated by $\{\epsilon_{1,k},\ldots,\epsilon_{4,k}\}_{k=1}^{t-1}$.[7]

Equation (17) provides a testing framework for our hypotheses. As discussed in introduction, the heat wave hypothesis claims that only the past domestic news predicts domestic volatility of exchange rates. The meteor shower hypothesis allows volatility spillovers and is the alternative. Thus, we can set

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[6]See the data appendix for the definition of $\epsilon_{i,t}$.

[7]If market j is closed on date s because of holidays, we set $\epsilon_{j,s}$ equal to zero in equation (17) on date s, for s = t or t-1. In doing so we assume that there is no public or private information released during holidays.

the null hypothesis of the heat wave to be $\alpha_{ij} = 0$ jointly for $j \neq i$ in equation (17). Furthermore, if the stochastic policy coordination is a major cause of the meteor shower, then the coefficient, α_{ij}, for $i \neq j$, measures the uncertainty of the domestic policy in response to the foreign policy shock, e.g. σ^2 or σ^{*2} in equation (16).

In addition to testing the heat wave hypothesis, we seek to measure the relative importance of the heat wave and meteor shower components of the variance. The strategy is to apply the technique of variance decompositions in a vector autoregressive model. In a sense, we propose a variance decomposition in the second moment. If the underlying process is stationary, taking the expectation of both sides of equation (17), we have[8]

$$h_i \equiv E(h_{i,t}) = \omega_i/(1-\beta_{ii}) + \sum_{j=1}^{4} \alpha_{ij} h_j/(1-\beta_{ii}) \quad \text{for } i = 1,\ldots,4 \qquad (18)$$

Dividing both sides by h_i gives a decomposition of the unconditional variance into five parts: $\omega_i/(1-\beta_{ii})h_i$, $\alpha_{ii}/(1-\beta_{ii})$ and $\alpha_{ij}h_j/(1-\beta_{ii})h_i$ for $j \neq i$, and $j=1,\ldots,4$. The sum of these ratios is one and each can be interpreted as a component of overall volatility in market i. The first is merely the source of constant time invariant volatility and is therefore not directly of interest. The second measures the strength of the heat wave effect on the overall variance. The remaining three give the average effect of volatility in market j on market i. The sum of these three is a measure of the importance of the meteor shower contribution to total volatility. The ratio of the meteor shower component to the heat wave component is a simple summary measure of the importance of the meteor shower in a particular market. As can be seen each of these

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[8]See Engle, Ito, and Lin (1989) for the necessary and sufficient conditions for the stationarity of the GARCH process.

estimated components is proportional to the estimated α's and therefore is a simple measure of how large the α's really are.

4. EMPIRICAL RESULTS

4.1 INTRA-DAILY YEN/DOLLAR EXCHANGE RATES AND POLICY REGIMES IN 1979–1988

The intra-daily yen/dollar exchange rate from February 1, 1979 to December 23, 1988 are considered in this paper. Daily changes in the yen/dollar rate are decomposed into four non-overlapping segments using closing and opening quotes in the New York and the Tokyo markets. We denote the change between the opening and the closing rates in Tokyo as the "TOKYO" segment. Since both the London and the New York markets are closed during the Tokyo segment, the Tokyo segment reflects mainly the Japanese news. Most participants do not trade during the time interval between the New York close and the Tokyo open, so we label this as a separate market segment denoted as "PACIFIC". The "NEW YORK" market segment is the change between the open and the close in New York, although the London market is still open during very early business hours of the New York market. The Europe market, "EUROPE", is represented by movements from the Tokyo close to the New York open.

Here, we consider two breaking points to take account of potential changes in policy coordination and the Japanese deregulation of capital controls within the 1979–1988 sample period. The first breaking point begins December 1, 1980 corresponding to the enactment of the Foreign Exchange and Foreign Trade Control Law which deregulated all the capital controls in Japan. (See Ito (1986) and Eken (1984).) For instance, Japanese residents were allowed to buy foreign securities without security firm's intermediation, and foreign companies were allowed to sell and buy the Japanese securities without any licensing.

The second breaking point is September 22, 1985 corresponding to the Plaza Agreement. This Agreement opened an era of policy coordination. Several steps in the ongoing coordinated exchange rate management among the industrial countries were taken to push the dollar down. As shown in Figure 1, the yen/dollar rate fluctuated within the range from 200 to 280 during the first two regimes. However, after the Plaza Agreement, the yen/dollar appreciated from 240 to 150 very quickly.

Following the Plaza meetings, the central banks of the Group of Five countries launched a concerted effort to conduct simultaneous sales of dollars with the aim of lowering the dollar's value to 200 (e.g., Obstfeld (1988) and Ito (1987,1988)). A further step in the policy coordination among these countries was taken in March and April of 1986. The group of five adopted coordinated discount rate cuts to "stimulate global growth without upsetting the exchange rate realignment" (e.g., Obstfeld (1988)). In October, the U.S. Treasury Secretary James A. Baker and the Japanese finance minister Kiichi Miyazawa reached an accord to maintain the exchange rate at a certain level reflecting market fundamentals. Further efforts to stabilize currency values brought about the Louvre accord on February 22, 1987 among G7 countries. These experiences of policy coordination may provide an explanation for the volatility clustering across the markets.

We summarize the relevant statistics describing our data set in Table 1. During our whole sample period, the dollar tends to depreciate in the Tokyo and the Europe markets and to appreciate in the New York and the Pacific markets. This depreciation or appreciation is not statistically significant in Tokyo and New York. However, the Pacific and the European markets show a significant drift in the yen/dollar movements.

A close look at the standard deviation shows that the New York market generally appears to be the most volatile market. The Tokyo market exhibits higher volatility than the other markets in the phase of capital controls. One of the possible explanations is that capital controls make Japanese traders concentrate trading in Tokyo.[9] The per-hour volatility is measured by the sample average of per hour squared changes of exchange rate movements. The business hours are adjusted to weekends, holidays and daylight saving time. The per-hour volatility also show that the Pacific market is the least volatile market. Moreover, some significant statistics of the skewness and the excess kurtosis indicate that the distribution of the intra-daily exchange rate is skewed and flat-tailed.

4.2 HEAT WAVES OR METEOR SHOWERS ?

We start with estimating the heat wave model for the four markets during the three policy regimes. After estimating, we compute the skewness and the excess kurtosis of the normalized residuals (e.g., $\epsilon_{i,t} / \hat{h}_{i,t}^{1/2}$) and then test for the normality (e.g., Kendall and Stuart (1958)). However, both statistics

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[9]The possible explanation is that the removal of the capital control may change the timing of trades. Extending trading in other markets will spread out the variance of the Tokyo market. Barclay, Litzenberger, and Warner (1988) found that the variance of stock returns in the Tokyo Stock Exchange is higher when it open on Saturday than when it is close, but the total variance during a week remain intact. Hence, they concluded that the variance is generated by private information.

appear too large to accept the null hypothesis although the results are not reported here. According to Bollerslev and Wooldridge's (1988) Monete Carlo experiments, the conventional Lagrange Multiplier test based on the regression of unity on the score has incorrect size under non-normality. Hence, they suggest the alterative procedure of the Lagrange Multiplier test that is robust to the non-normality. Such robust Lagrange Multiplier tests for meteor showers are reported in the middle parts of Tables 2 to 5. The test for meteor showers is much like a Granger causality test for variances where the own lag is significant until the intervening variables are introduced. Several inferences can be drawn from the test statistics.

First, the rejection of the heat wave hypothesis in the third regime is not surprising. It is in accordance with the results in Engle, Ito, and Lin (1990) for the yen/dollar rate, and Lin (1989) for the yen/dollar, the mark/dollar, and the pound/dollar rates during the one year period after the Plaza Agreement. The rejection also discredits the deterministic policy coordination as shown in Section 2. Because the direction and the magnitude of the reaction to the foreign policy shock are known, there would be no meteor showers. [10] Second, as discussed in the introduction, stochastic policy coordination, gradual revelation of private information, or market failures such as bandwagons or fads, can lead to volatility clustering of exchange rates across markets. Findings of meteor showers during 1985–1988 cannot differentiate these two interpretations.

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[10]The paper by Ito and Roley (1988) showed that the random walk behavior was rejected during 1980–1986 period and the economic significance of the departures from the random walk model declined after the Plaza meetings. The results would again rule out the possibility of the deterministic policy coordination.

Nevertheless, the significant statistics in regime two, the period without policy coordination, support the view that the stochastic policy coordination is not a major cause of the meteor shower. Finally, the volatility of the Tokyo market does not exhibit a meteor shower during the period of capital controls. The result implies that the capital controls prevent foreign investors from trading in the Tokyo market and then mitigate the meteor shower effect in Tokyo.

Estimated results of the meteor shower models for the four markets are reported in the top parts of Tables 2 to 5 according to the specification of equation (17). The skewness and the excess kurtosis of the normalized residuals are also summarized. Although in most cases they become smaller as compared with the results for the raw data in Table 1, the normality hypothesis cannot still be accepted.[11] As the assumption of normality is violated, the score of the normal-log likelihood still has the martingale difference property under fairly general regularity conditions provided only that the first two conditional moments are correctly specified. Hence, the estimators remain consistent but the conventional standard errors computed form the outer product of the score are not valid. We report the robust standard errors of the quasi-maximum likelihood estimators according to Bollerslev and Wooldridge's formula (1989) in Tables 2 - 5. In general, the robust standard errors are much larger than the conventional ones. Some impacts of meteor showers become insignificant. By

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[11]Note that the data in Table 1 are not adjusted to the daylight saving time and weekends. Since the Pacific market includes weekends, the results in Table 1 and Table 2 are not comparable. Using the same data set as in Table 2, the (excess) kurtosis for the raw residuals are 8.0304, 36.2480, and 13.0042, and the skewness are 0.4774, 2.0671, 0.4221 for the first, the second, and the third regimes, respectively.

examining the t statistic for the impact of the foreign shock on the volatility, we can find the foreign shock significantly spilling over to the Pacific, the Europe, and the New York markets during the first regime, while the joint tests do not show the significant effects.

A glance at the coefficient of domestic news on the volatility of exchange rates (i.e., the heat wave effect) reveals that this impact is monotonically decreasing. Moreover, the impact of Tokyo news on exchange rate volatility around the world appears to be greater after the removal of capital controls. These findings lead to two interesting questions; did the removal of capital controls increase the impact of Tokyo news on the volatility of exchange rates, and what is the relative importance of heat waves to meteor showers in exchange rate volatility over the three regimes? The two issues will be examined in the next section.

5. VARIANCE DECOMPOSITIONS AND DIAGNOSTIC TESTS

5.1 RELATIVE IMPORTANCE OF NEWS IN VARIANCE

In this section we apply the second moment variance decompositions to evaluate the contribution of country-specific news to the volatility of exchange rates. The variance decompositions measure the proportion of country-specific news in explaining volatility within the sample period. If one country-specific news is more important in generating exchange rate volatility than other news, we can expect the proportion of this country variance in total variance to be large. The middle parts of Table 2 through Table 5 present the empirical results.

Examining the statistics on the variance decompositions shows that meteor showers have the largest proportion of volatility of the Pacific and the New

York markets in regime three, but of the volatility of the Tokyo and the European markets in regime two. The component due to the heat wave is the smallest in the third period for all markets. Thus over time, global volatility spillovers have become relatively more important as determinants of volatility. This may be attributable to increased policy coordination, even though this is not the only cause of meteor showers as judged by the rejection of the heat wave model in the second regimes.

Tables 2 – 5 show also that the proportion of Tokyo news in total variance increases after the Japanese deregulations of capital controls in the four markets. This empirical evidence can be attributed to the fact that the liberalization of the Tokyo market reinforces the impact of Tokyo news as well as to the growing economic power of Japan.

5.2 DIAGNOSTIC TESTS

We report two sets of diagnostic tests in the bottoms of Table 2 through Table 5. The first set of tests checks the stability of volatility processes. Since there are substantial policy switches over the 1979–1988 periods, they may have significantly different influences on the stochastic behavior of exchange rates. Indeed, Roley (1987), Ito and Roley (1987,1988) found substantial differences in the response of exchange rates or interest rates to various economic news across regimes.

The likelihood ratio tests check whether the meteor shower models are stable across two adjacent regimes and the whole sample period. Significant statistics at least at a 1% level show the instability of meteor showers across the policy regimes, indicating structural changes in the volatility processes.

The second set of tests investigates the geographic impact of news on volatility. The alternative view of the meteor showers is that market behaves as if there is continuous trading and news over the twenty-four hour period. If news itself is effectively a meteor shower then the volatility of the exchange rate should be a meteor shower. An example is the real meteor shower because of the linkage of the real economies.

In order to test this hypothesis, we stack sequentially all the observations in the Pacific, the Tokyo, the European, and the New York markets to form a world market. Since the impact of news on the volatility has a time delay, we estimate the GARCH (4,4) model for this world-wide market. The world-wide model is nested within the meteor shower models in the first panel of Tables 2 – 5. The likelihood ratio tests in Table 5 show the rejection of the meteor shower models with world-wide news at a 1% level, indicating that the impact of news is subject to terrestrial geography.

6. CONCLUSIONS

This paper extends Engle et al.(1988) to discuss the intra-daily volatility process of the yen/dollar exchange rate across different regimes defined by the Japanese abolition of capital controls in December 1980 and the era of policy coordination after the Plaza Agreement in September 1985. Several conclusions emerge from this study.

First, the hypothesis tests show that the heat wave hypothesis is soundly rejected across the second and the third regimes, and the markets. The rejection is unlikely to be attributable to stochastic policy coordination since the second regime is supposed to have little coordination. The test also show that the heat wave model is acceptable in the Tokyo market during the capital control period, implying that capital controls did prevent the meteor showers in

Tokyo.

Second, examining the variance decompositions we find not only that the meteor shower effect is intensified in the stochastic policy coordination regime, but also that the removal of capital controls increases the impact of Tokyo news on volatility by integrating the Tokyo market into the world markets.

Finally, diagnostic tests show that this volatility process of the exchange rate appears to undergo structural changes over regimes. The hypothesis tests also support the view that news is country–specific.

APPENDIX: DATA SOURCES AND DEFINITIONS

The data used in the paper are defined as follows:

TKO(t) = the opening (9 AM) yen/dollar quote in the Tokyo foreign exchange market on date t.

TKC(t) = the closing (3:30 PM) yen/dollar quote in the Tokyo foreign exchange market on date t.

NYO(t) = the opening (9 AM) yen/dollar quote in the New York foreign exchange market on date t.

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

All quotes are in the logarithm of yen/dollar. Tokyo quotes are collected daily from *Nihon Keizai Shinbun*, which are the transaction rates. New York quotes are the simple average of bid and ask rates given by the Federal Reserve Bank of New York.

The market segments are defined as the following:

$\epsilon_{TK,t} = (TKC(t) - TKO(t))/\sqrt{6.5}$

$\epsilon_{NY,t} = (NYC(t) - NYO(t))/\sqrt{7.5}$

$\epsilon_{EU,t} = (NYO(t) - TKC(t))/\sqrt{6.5}$ during the daylight saving time

$= ((NYO(t) - TKC(t))/\sqrt{7.5}$ otherwise

During weekdays, changes in Pacific are defined as

$\epsilon_{PA,t} = (TKO(t) - NYC(t-1))/\sqrt{3.5}$ during the daylight saving time

$= (TKO(t) - NYC(t-1))/\sqrt{2.5}$ otherwise

During weekends, changes in Pacific are defined as

$\epsilon_{PA,t} = (TKO(t) - NYC(t-1))/\sqrt{51.5}$ during the daylight saving time

$= (TKO(t) - NYC(t-1))/\sqrt{50.5}$ otherwise

The daylight saving time starts from the last Sunday of April to the last Sunday of October in New York every year.

TABLE 1 DATA SUMMARY

Market	Pacific	Tokyo	Europe	New York
Regime 1: February 1, 1979 – November 30, 1980				
Mean	0.0515	0.0128	-0.0642	0.0153
(T-Stat)	(7.2179)	(0.5949)	(-3.4035)	(0.8814)
St. Deviation	0.1492	0.4594	0.3950	0.3699
Skewness[d]	0.2303[b]	-1.2745[a]	-0.8551[a]	-0.9474[a]
Kurtosis[d,e]	5.4329[a]	9.3998[a]	6.4071[a]	4.0045[a]
Per Hour Var	0.0059	0.0324	0.0230	0.0182
Regime 2: December 1, 1980 – September 21, 1985				
Mean	0.0231	0.0064	-0.0388	0.0177
(T-Stat)	(4.6002)	(0.7020)	(-3.8199)	(1.4560)
St. Deviation	0.1709	0.3181	0.3461	0.4210
Skewness	1.2577[b]	-0.4407[a]	0.0310	-0.2695[a]
Kurtosis	18.1025[a]	3.3311[a]	3.0086[a]	1.6821[a]
Per Hour Var	0.0065	0.0156	0.0175	0.0236
Regime 3: September 22, 1985 – December 23, 1988				
Mean	-0.0205	-0.0176	-0.0231	-0.0120
(T-Stat)	(-2.0239)	(1.4104)	(-1.8120)	(-0.8222)
St. Deviation	0.2823	0.3553	0.3562	0.4175
Skewness	-0.0252	-0.1134	-0.0848	-0.4153[a]
Kurtosis	7.7219[a]	3.7064[a]	3.0526[a]	4.1530[a]
Per Hour Var	0.0183	0.0190	0.0184	0.0233
Whole : February 1, 1979 – December 23, 1988				
Mean	0.0140	-0.0003	-0.0383	0.0074
(T-Stat)	(3.2180)	(0.0381)	(-5.2087)	(0.8983)
St. Deviation	0.2125	0.3602	0.3590	0.4100
Skewness	0.1195[b]	-0.6613[a]	-0.2309[a]	-0.4121[a]
Kurtosis	12.7591[a]	6.8723[a]	4.0182[a]	3.0364[a]
Per Hour Var	0.0103	0.0198	0.0188	0.0225

(a) significant at a 1% level.
(b) significant at a 5% level.
(c) Variables are the percent changes in the logarithm of the yen/dollar exchange rate.
(d) Two-tailed tests under the null hypothesis of normal distribution; see Kendall and Stuart (1958).
(e) Excess kurtosis adjusted to the standard normal distribution.

TABLE 2 TEST AND ESTIMATION FOR METEOR SHOWERS: PACIFIC

Model:

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

$$h_{PA,t} = \omega_1+\beta_{11}h_{PA,t-1}+\alpha_{11}\epsilon^2_{PA,t-1}+\alpha_{12}\epsilon^2_{TK,t-1}+\alpha_{13}\epsilon^2_{EU,t-1}+\alpha_{14}\epsilon^2_{NY,t-1}$$

Regimes	R1	R2	R3
Constant	0.0008[b,c] (0.0004)	0.0001[c] (0.0001)	0.0003[c] (0.0003)
$h_{PA,t-1}$	0.3020[b,c] (0.1538)	0.5308[b,c] (0.1221)	0.3736[a,c] (0.0362)
$\epsilon^2_{NY,t-1}$	0.0507[c] (0.0288)	0.0390[c] (0.0369)	0.0916[b,c] (0.0458)
$\epsilon^2_{EU,t-1}$	0.0338[b,c] (0.0159)	0.0112[c] (0.0094)	0.0485[c] (0.0266)
$\epsilon^2_{TK,t-1}$	0.0001 (0.0002)	0.0637[b,c] (0.0298)	0.3405[a,c] (0.1172)
$\epsilon^2_{PA,t-1}$	0.4129[c] (0.2411)	0.1717[a,c] (0.0577)	0.1838[c] (0.1062)
Skewness	−0.0639	0.5023[a]	0.2510[a]
(Excess) Kurtosis	7.5624[a]	10.2493[a]	8.8929[a]
RB LM Test for Meteor Showers[d]	1.8885	4.2103	9.1198[b]
Variance Decompositions:			
Meteor Showers:			
Tokyo News:	0.0008	0.3258	0.5644
Europe News:	0.1888	0.0643	0.0779
New York News:	0.2241	0.3018	0.1862
Sum of Meteor Showers:	0.4137	0.6919	0.8284
Heat Waves:	0.5915	0.3659	0.2934
Meteor Showers/Heat Waves:	0.6992	1.8907	2.8233
Test for Stability:[e]	49.8618[a]	169.6494[a]	263.8251[a]

(a) indicates that the robust t statistic (or the normality test)is significant at a 1% level.
(b) indicates that the robust t statistic (or the normality test) is significant at a 5% level.
(c) indicates that the conventional t statistic is significant at a 5% level.
(d) indicates the robust Lagrange multiplier test distributed as $\chi^2(3)$. The critical values are 6.25 (10%), 7.81 (5%), and 11.3 (1%).
(e) The first column tests for stability in regime 1 and regime 2, the second column tests for stability in regime 2 and regime 3, and the third column tests for stability in the whole sample period.

TABLE 3 TEST AND ESTIMATION FOR METEOR SHOWERS: TOKYO

Model:

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

$$h_{TK,t} = \omega_2+\beta_{22}h_{TK,t-1}+\alpha_{21}\epsilon^2_{PA,t}+\alpha_{22}\epsilon^2_{TK,t-1}+\alpha_{23}\epsilon^2_{EU,t-1}+\alpha_{24}\epsilon^2_{NY,t-1}$$

Regimes	R1	R2	R3
Constant	0.0054[c]	0.0001	0.0048[a,c]
	(0.0038)	(0.0002)	(0.0017)
$h_{TK,t-1}$	0.2878[c]	0.6658[a,c]	0.3694[a,c]
	(0.1768)	(0.0503)	(0.1258)
$\epsilon^2_{PA,t}$	0.2863	0.0184	0.0985[b,c]
	(0.2354)	(0.0241)	(0.0462)
$\epsilon^2_{NY,t-1}$	0.1444	0.0576[a,c]	-0.0003
	(0.0872)	(0.0213)	(0.0018)
$\epsilon^2_{EU,t-1}$	0.2026[c]	0.0474[a,c]	0.1574[a,c]
	(0.1074)	(0.0184)	(0.0581)
$\epsilon^2_{TK,t-1}$	0.2739[a,c]	0.2182[a,c]	0.1568[a,c]
	(0.0981)	(0.0426)	(0.0604)
Skewness	-0.1155	-0.1359	-0.4624[a]
(Excess) Kurtosis	3.7276[a]	1.9669[a]	3.3435[a]
RB LM Test for Meteor Showers[d]	2.7762	8.9987[b]	9.3888[b]
Variance Decompositions:			
Meteor Showers:			
Pacific News:	0.0732	0.0229	0.1504
Europe News:	0.2019	0.1591	0.2417
New York News:	0.1139	0.2607	-0.0006
Sum of Meteor Showers:	0.3890	0.4427	0.3915
Heat Waves:	0.3846	0.6529	0.2487
Meteor Showers/Heat Waves:	1.0116	0.6782	1.5748
Test for Stability:[e]	85.2077[a]	93.0794[a]	133.8531[a]

(a) to (e): see Table 2

TABLE 4 TEST AND ESTIMATION FOR METEOR SHOWERS: EUROPE

Model:

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

$$h_{EU,t} = \omega_3+\beta_{33}h_{EU,t-1}+\alpha_{31}\epsilon^2_{PA,t}+\alpha_{32}\epsilon^2_{TK,t}+\alpha_{33}\epsilon^2_{EU,t-1}+\alpha_{34}\epsilon^2_{NY,t-1}$$

Regimes	R1	R2	R3
Constant	0.0044[c]	0.0006[c]	0.0020[c]
	(0.0025)	(0.0004)	(0.0015)
$h_{EU,t-1}$	0.4180[b,c]	0.8252[a,c]	0.8478[a,c]
	(0.1676)	(0.0751)	(0.0928)
$\epsilon^2_{TK,t}$	0.0843[b,c]	0.0595[b,c]	0.0274[c]
	(0.0382)	(0.0241)	(0.0252)
$\epsilon^2_{PA,t}$	0.4682[c]	-0.0113	0.0134
	(0.4118)	(0.0114)	(0.0137)
$\epsilon^2_{NY,t-1}$	0.0916[c]	0.0313[b,c]	0.0010
	(0.1125)	(0.0151)	(0.0007)
$\epsilon^2_{EU,t-1}$	0.1163[c]	0.0502[c]	-0.0014
	(0.0836)	(0.0386)	(0.0179)
Skewness	-0.2610[b]	-0.0897	-0.2281[a]
(Excess) Kurtosis	2.6727[a]	2.4104[a]	3.5442[a]
RB LM Test for Meteor Showers[d]	5.1475	14.6788[a]	6.4667
Variance Decompositions:			
Meteor Showers:			
Pacific News:	0.2064	-0.0240	0.0876
Tokyo News:	0.2040	0.3034	0.1859
New York News:	0.1245	0.2415	0.0083
Sum of Meteor Showers:	0.5349	0.5209	0.2818
Heat Waves:	0.1998	0.2872	-0.0092
Meteor Showers/Heat Waves:	2.6770	1.8138	-30.6335
Test for Stability:[e]	35.3539[a]	39.9548[a]	71.9204[a]

(a) to (e): see Table 2.

TABLE 5 TEST AND ESTIMATION FOR METEOR SHOWERS: NEW YORK

Model:

$$\epsilon_{NY,t} \mid \psi_{NY,t} \sim N(0,h_{NY,t})$$
$$h_{NY,t} = \omega_4+\beta_{44}h_{NY,t-1}+\alpha_{41}\epsilon^2_{PA,t}+\alpha_{42}\epsilon^2_{TK,t}+\alpha_{43}\epsilon^2_{EU,t}+\alpha_{44}\epsilon^2_{NY,t-1}$$

Regimes	R1	R2	R3
Constant	0.0005	0.0016	-0.0001
	(0.0003)	(0.0011)	(0.0001)
$h_{NY,t-1}$	0.8035[a,c]	0.7816[a,c]	0.9679[a,c]
	(0.0342)	(0.0714)	(0.0078)
$\epsilon^2_{EU,t}$	0.0287[c]	0.0736[c]	0.0595[a,c]
	(0.0164)	(0.0421)	(0.0096)
$\epsilon^2_{TK,t}$	0.0070[a,c]	0.0697[b,c]	-0.0001[c]
	(0.0020)	(0.0290)	(0.0001)
$\epsilon^2_{PA,t}$	0.0995	-0.0274[b]	0.0638[a,c]
	(0.0998)	(0.0134)	(0.0086)
$\epsilon^2_{NY,t-1}$	0.0911[c]	0.0629[a,c]	-0.0541[a,c]
	(0.0552)	(0.0208)	(0.0106)
Skewness	-0.3522[a]	-0.5220[a]	0.0220
(Excess) Kurtosis	2.0709[a]	3.2592[a]	2.3269[a]
RB Test for Meteor Showers[d]	6.5717	14.8827[a]	22.1393[a]
Variance Decompositions:			
Meteor Showers:			
Pacific News:	0.1642	-0.0346	1.5610
Tokyo News:	0.0634	0.2110	-0.0025
Europe News:	0.1846	0.2499	1.4638
Sum of Meteor Showers:	0.4121	0.3370	3.0223
Heat Waves:	0.4636	0.4263	-1.6854
Meteor Showers/Heat Waves:	0.8890	1.2650	-1.7932
Test for Stability:[e]	43.8629[a]	80.8930[a]	118.5204[a]
Test for Meteor Showers with World-Wide News:[f]	427.0076[a]	626.1027[a]	329.4778[a]

(a) to (e): see Table 2.
(f) H_0: the meteor showers with world-wide news, i.e., $\omega_1=\omega_2=\omega_3=\omega_4$, $\beta_{11}=\beta_{22}=\beta_{33}=\beta_{44}$, $\alpha_{11}=\alpha_{22}=\alpha_{33}=\alpha_{44}$, $\alpha_{12}=\alpha_{23}=\alpha_{34}=\alpha_{41}$, $\alpha_{13}=\alpha_{24}=\alpha_{31}=\alpha_{42}$, $\alpha_{14}=\alpha_{21}=\alpha_{32}=\alpha_{43}$.

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