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**Heat Waves, Meteor Showers, and Trading Volume:
An Analysis of Volatility Spillovers in the U.S. Treasury Market***

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Abstract

The market for U.S. Treasury securities operates around-the-clock from the three main trading centers of Tokyo, London, and New York. We examine this market for volatility spillovers using the methodology employed by Engle, Ito, and Lin (1990) for the foreign exchange market. We find meteor showers in Tokyo and London but not New York; i.e., volatility spills over into Tokyo and London from the other trading centers, but not into New York. We also find that lagged trading volume significantly impacts U.S. Treasury yield volatility for the overseas trading centers, although it does not change the basic meteor shower findings.

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I. Introduction

U.S. Treasury securities are traded around-the-clock in the three main trading centers of Tokyo, London, and New York. Given this market structure, Treasury yields can readily incorporate economic announcements and other developments when they actually occur. On August 27, 1998, for example, U.S. Treasury yields fell sharply in the overseas trading centers amid tumbling foreign equity markets, Russia's suspension of trading in the ruble, and reports of weak economic growth from South Korea and Malaysia. When financial markets opened in New York, Treasury yields continued to fall as U.S. equity markets dropped sharply.¹ In this paper, we examine the issue of linkages between financial trading centers in a round-the-clock market by examining U.S. Treasury yield volatility spillovers across the three trading centers.

To date, study of volatility spillovers across trading centers has focused on the foreign exchange market, which also trades around-the-clock in several sites.² Engle, Ito, and Lin (1990) propose two hypotheses on how volatility might manifest itself across trading centers. The "heat wave" hypothesis is that volatility has only location-specific autocorrelation so that a volatile day in New York is likely to be followed by another volatile day in New York, but not typically a volatile day in Tokyo. The alternative "meteor shower" hypothesis is that intraday volatility spills over from one trading center to another so that a volatile day in New York is likely to be followed

¹ See "U.S. Bonds Rise on Emerging Market Doubt, Falling Stock Market," Bloomberg, August 27, 1998 7:20 a.m. (New York time) and "U.S. Bonds Rally, Yields Fall to Record Low as Stocks Tumble," Bloomberg, August 27, 1998 3:25 p.m.

² There is also an extensive, related literature that examines volatility spillovers across trading centers for different assets, albeit of the same class. See, for example, Baillie and Bollerslev (1990) for foreign exchange; Hamao, Masulis, and Ng (1990) for equity markets; and Singleton (1991) for interest rates.

by a volatile day in Tokyo. Using a GARCH model to test for the spillover of volatility across intraday trading segments, they find evidence in favor of the meteor shower hypothesis such that yen/dollar volatility spills over from one trading center to another as the global trading progresses.

The U.S. Treasury market offers an interesting, alternative testing ground for these hypotheses on volatility spillovers. Since the Treasury market operates around-the-clock from different trading centers, the methodology of Engle *et al.* (1990) can be applied with only minor modifications. However, the intraday behavior of Treasury yields differs markedly from that of exchange rates and, in particular, seems dominated by events that occur during New York trading hours. Analysis of the Treasury market therefore offers the opportunity to examine the nature of volatility spillovers in a distinct market with different information flows.

In this paper, we examine the U.S. Treasury market for volatility spillovers across the three main trading centers. We first test for the GARCH form of heteroskedasticity in within market yield changes (i.e., the yield change across a center's trading hours) and find that volatility does indeed persist in each of the three trading centers. We then examine whether information accumulated during out-of-market trading hours impacts the intramarket variance. We find that the volatility dynamics are best characterized by the meteor shower hypothesis in Tokyo and London, with volatility spilling into these markets from the other trading centers. In contrast, the volatility in New York is best characterized by the heat wave hypothesis, as little evidence is found that volatility spills into New York from the overseas markets.

Our results contrast with those of the foreign exchange market where meteor showers are found for every major trading center, including New York. Differences in information arrival may explain these divergent results. While per-hour yen/dollar volatility is fairly steady across the different trading locations (Engle *et al.* (1990)), volatility in the U.S. Treasury market is highly

concentrated during New York trading hours (Fleming (1997)). Furthermore, the high New York volatility seems to emanate from events that occur during New York trading hours (Fleming and Remolona (1997)). Spillovers from New York into the overseas trading centers therefore seem more likely to occur and easier to detect than spillovers from the overseas trading centers into New York.

Finally, we test whether the addition of lagged trading volume improves the fit of the volatility models and the extent to which this addition impacts our basic findings. Although the impact of news on financial time series is generally examined by modeling the conditional volatility of the series, alternative indicators are available and have been used to examine information flows into a market (e.g., Bollerslev and Domowitz (1993)). We choose trading volume because it is generally considered to be a good proxy for the degree of heterogeneity in traders' beliefs. We find that lagged, intramarket trading volume significantly improves volatility estimates for the overseas locations, although it does not impact our basic finding of meteor showers for these markets. The presence of both effects raises interesting questions about the microstructure of the U.S. Treasury market.

The paper is organized as follows. The U.S. Treasury market and our data source is described in the next section. The methodology and empirical results for the basic volatility spillover models are presented in Section III. Trading volume is introduced into the volatility models in Section IV. Section V contains a summary of our findings and concluding remarks.

II. The 24-Hour Market for Treasury Securities

A. Market Description

Trading in U.S. Treasury securities takes place in a multiple dealer, over-the-counter market.³ The predominant market makers are the 29 primary government securities dealers-- financial firms with which the Federal Reserve Bank of New York interacts directly in the course of its open market operations. For the April-August 1994 period, the dealers traded an average of \$125.5 billion of securities per day: \$67.0 billion with customers, and \$58.5 billion with other dealers (Fleming (1997)). The core of the U.S. Treasury market, and the source of our data, is the interdealer broker market, which accounts for over 90% of trading between dealers (or \$53.5 billion per day). Interdealer brokers collect and post dealer quotes and execute trades between dealers, thereby facilitating information flows in the market while providing anonymity to the trading dealers.⁴ The brokered market is extremely liquid with *minimum* trade sizes of \$1 million, average bid-ask spreads of about 1/64 of a point for the on-the-run five-year Treasury note (about 0.4 basis points in yield), and modest brokerage fees.⁵

Trading takes place twenty-three hours per day during the week, from three major trading locations (Figure 1).⁶ The global trading day begins at 8:30 a.m. local time in Tokyo, which is 6:30 p.m. New York standard time (ST). Trading continues until roughly 5 p.m. local time in

³ Additional sources on the U.S. Treasury market are U.S. General Accounting Office (1986), Bollenbacher (1988), Stigum (1990), U.S. Department of the Treasury *et al.* (1992), Madigan and Stehm (1994), and Fleming (1997).

⁴ The major interdealer brokers are Cantor Fitzgerald Securities, Exco USA Securities, Inc., Garban GuyButler Inc., Hilliard Farber & Co., Inc., Liberty Brokerage Inc., and Tullett & Tokyo Securities, Inc.

⁵ On-the-run securities (also called *active* or *current*) are the most recently issued securities of a given maturity. See Fleming (1997) for bid-ask spread descriptive statistics and Stigum (1990) for interdealer brokerage fees.

⁶ Trading decreases to twenty-two hours per day when New York switches to eastern daylight saving time. There is no trading on weekends.

Tokyo (3 a.m. New York ST), when trading passes to London, where it is 8 a.m. At about 12:30 p.m. local time in London, trading passes to New York, where it is 7:30 a.m.⁷ Trading continues in New York until roughly 5:30 p.m. Regardless of location, the trading process for U.S. Treasuries is the same; the same securities are traded by the same dealers through the same interdealer brokers with the same brokerage fees. Trades agreed upon during the Tokyo and London trading hours typically settle as New York trades do--one business day later in New York through the Government Securities Clearance Corporation.

In contrast to the foreign exchange market, where yen/dollar volatility is of similar magnitudes across the three major trading locations, U.S. Treasury market volatility is highest during the New York trading hours. Engle *et al.* (1990) report variances of 0.42, 0.46, and 0.57 for the Tokyo, Europe, and New York markets, respectively, for the log differenced yen/dollar exchange rate. In comparison, Fleming (1997) finds that the average absolute price change for the on-the-run five-year U.S. Treasury note is just over 8/32 of a point for the New York session (about 6.2 basis points in yield), but just under 2/32 of a point for both the Tokyo and London sessions (about 1.4 basis points). Trading volume in the U.S. Treasury market is highly concentrated as well, with roughly 94% of trading in New York, on average, about 4% in London and 2% in Tokyo. Such a concentration may be explained by the macroeconomic announcements released during New York trading hours, which lead to sharp price revisions and trading volume surges (Fleming and Remolona (1997, 1999). The fixed hours of Treasury futures trading on the Chicago Board of Trade (8:20 a.m. - 3 p.m., New York ST) and the predominance of U.S.

⁷ As this is an over-the-counter market, the crossover times are necessarily approximate. Traders in London may continue to transact during their afternoon while morning activity picks up in New York. In addition, traders may transact from one location during another location's business hours (e.g., from New York during Tokyo business hours).

individuals and institutions as owners of Treasury securities may also be important to explaining this concentration.

B. Data

Our data cover two and a half years of trading activity in the interdealer broker market. The source of the data is GovPX, Inc., a joint venture set up by the primary dealers and interdealer brokers in 1991 to improve the public's access to U.S. Treasury security prices. GovPX consolidates and posts real-time quote and transactions data from five of the six major interdealer brokers, accounting for roughly two-thirds of the interdealer broker market.⁸ Posted data include the best bids and offers, trade prices and sizes, and the aggregate volume of trading for all Treasury bills, notes, and bonds. GovPX data are distributed electronically to the public through several on-line vendors.

Our sample period is February 24, 1992 to August 19, 1994. After excluding 13 non-trading days and 2 days of missing data, we are left with a sample of 635 trading days.⁹ Our analysis focusses on the on-the-run, five-year U.S. Treasury note, although we conduct robustness tests using the two- and ten-year notes. The five-, two-, and ten-year notes are the three most actively traded securities in our sample, accounting for 25.6%, 19.6%, and 15.7% of on-the-run trading volume, respectively, and are the most actively traded, in the same order, for each of the three major trading centers. While Treasury notes are quoted and traded in points

⁸ Cantor Fitzgerald Securities, which specializes in longer-term securities and in particular the thirty-year bond, is not included.

⁹ The 13 non-trading days include 11 days when GovPX reports zero trading volume and 2 days when it reports negligible trading volume (\$3 million and \$4 million, total). The missing days of data (December 24, 1992 and December 31, 1992) are characterized by an early market close and an absence of major economic announcements.

(where one point equals one percent of par), our analysis is conducted in terms of yields, which are calculated from the transacted point price and included in the GovPX dataset.¹⁰ Daily closing New York transaction yields of the five-year note over the sample period are plotted in Figure 2.

We consider the intraday yield changes for the three market segments corresponding to the three major trading centers, as shown in Figure 1. Each segment's yield change is calculated as the difference between the last transaction yield of that center's trading hours and the last transaction yield of the previous center's trading hours. Missing yields due to holidays in individual trading centers are filled in with the last yield of the previous trading center in the round-the-clock market, effectively imposing a zero yield change for that market segment. In addition, the yield change is adjusted to account for changes in the on-the-run security. The on-the-run yield generally jumps up or down when the on-the-run security changes due to differences in maturity, liquidity, and cost-of-carry between the old and the new on-the-run securities. To correct for this, we collected yield data from the when-issued market for the new securities. This additional data allows the security yields to overlap in our dataset, so that all yield changes can be calculated using data from the same security.¹¹ Once the yield changes are calculated, per-hour volatility for each segment is computed as the squared intraday yield change divided by the number of trading hours in that market. The length of the Tokyo market is measured from the

¹⁰ The dataset is filtered for errors by eliminating trade-to-trade yield changes of 10 basis points or more that are followed by similarly sized yield changes (75-133% of the preceding change) in the opposite direction. The 10 basis-point threshold, which is somewhat arbitrary, is roughly the size of the largest actual trade-to-trade yield changes during the sample period.

¹¹ For example, on the last day a security is on-the-run, the New York yield change is calculated in the standard way as the difference between the last yield in New York and the last yield in London for the same on-the-run security. When the on-the-run security changes with the new trading day in Tokyo, the Tokyo yield change is calculated as the difference between the last yield in Tokyo on the new on-the-run security and the last yield in New York on the same security (even though that security was not yet on-the-run during the New York hours). Note that Amin and Ng (1997) make a similar adjustment to account for switches due to expirations in their examined futures contracts, although they estimate a coefficient for their switch adjustment.

New York close excluding weekend hours.¹²

Descriptive statistics for the five-year note's intraday yield changes and trading volume are presented in Table 1. The preponderance of yield movements during New York trading hours is clearly demonstrated by the per hour, yield change variances: 0.3 in Tokyo, 0.6 in London, and 4.1 in New York. The level of trading volume for the five-year note also shows the preponderance of activity in New York, with per hour means of \$13 million (principal value) in Tokyo, \$52 million in London, and \$448 million in New York. Table 1 also reveals a mean yield change during London trading hours that is statistically significant at the 5% level, albeit small economically at just 0.2 basis points. Statistical tests also indicate skewness in Tokyo and New York (both at the 5% level of significance), excess kurtosis in all three markets (all significant at the 5% level), and serial correlation in London (at the 10% level of significance).

Further descriptive evidence on the behavior of the Treasury market by trading center is presented in Table 2. The table shows the largest absolute yield changes for each trading center during our sample period along with the information cited in the press as causing the change. As shown in Panels A and B of Table 2, large yield changes in the overseas markets are attributed to overseas developments in other markets, U.S. political or policy developments that take place during U.S. overnight hours, press reports of possible U.S. policy changes released during the overnight hours, and other factors. In contrast, Panel C of Table 2 shows that the largest yield changes in New York are all attributed to major macroeconomic announcements. Table 2 also

¹² The length of the Tokyo market is complicated by two factors: the one or two hours of non-trading time between the New York close and the Tokyo open on weekdays and the weekend hours between New York's Friday close and Tokyo's Monday open. Since the weekday non-trading hours are so few, they are incorporated into the Tokyo trading hours. We exclude the weekend hours, effectively imposing a zero yield change. Analysis of yield changes over these hours indicates that although information arrives on weekends (i.e. the yield change is not always zero), average per-hour information arrival is substantially less than during Tokyo trading hours.

shows that the absolute size of the yield changes is substantially greater in New York than in Tokyo or London, consistent with the statistical evidence in Table 1.

III. Testing for Volatility Spillovers in the U.S. Treasury Market

A. *Econometric Models and Hypothesis Tests*

There exist a wide variety of models that attempt to characterize the dynamics of interest rates, but as noted by Chan, Karolyi, Longstaff, and Sanders (1992), many such models are nested within the stochastic differential equation

$$dy = (\mu + \rho y)dt + f(\sigma) dW,$$

where y denotes the interest rate, $f(\sigma)$ denotes the variance of the innovation to y , and W is a standard, Brownian motion. The discrete-time specification of this model is

$$\Delta y_t = y_t - y_{t-1} = \mu + \rho y_{t-1} + \varepsilon_t,$$

where $E_{t-1}[\varepsilon_t] = 0$ and $E_{t-1}[\varepsilon_t^2] = h_t$. This model specification is employed by Chan *et al.* (1992); Brenner, Harjes, and Kroner (1996); and Amin and Ng (1997).

We employ this model specification to examine the daily yields for the five-year U.S. Treasury note. Daily yield changes are measured for each trading center by the 24-hour yield change recorded at each market's close. We first test for the presence of a unit root (i.e., $\rho = 0$) using the augmented Dickey-Fuller test statistics. These tests do not reject the null hypothesis at the 10% level. The daily yield changes are also examined using standard regression analysis with White standard errors, which are robust against unspecified heteroskedasticity in ε_t . The estimation results indicate that neither μ nor ρ are significant at the 10% level for any of the series, matching results previously observed in the literature. Going forward, we assume that no

conditional mean dynamics are present in the differenced yield data.¹³

The specification of the conditional variance h_t is what generally defines the various classes of interest rate models. To analyze volatility spillovers in the foreign exchange market, Engle *et al.* (1990) specify h_t using adaptations of the GARCH model developed by Engle (1982) and Bollerslev (1986). We follow the framework of Engle *et al.* (1990) to analyze volatility spillovers in the U.S. Treasury market.

The daily market for Treasury securities is divided into three non-overlapping market segments denoted as the Tokyo, London, and New York trading centers, as defined above. The yield changes during each market segment are normalized by dividing them by the square root of the number of trading hours in that segment; thus

$$\varepsilon_{i,t} = \frac{y_{i,t} - y_{i-1,t}}{\sqrt{\tau_i}},$$

where $y_{i,t}$ is the closing yield in market segment i on date t , and τ_i is the number of trading hours in market segment i . (Note that if segment i is the first of the day, the previous yield term is that of the last market segment of the previous day.) Since we define the market segments such that they open and close sequentially, the information set available at the open of one segment contains all of the trading information revealed during the previous segment.

The GARCH specification used to test for the presence of volatility spillovers models the per-hour conditional variance of the three segments' yield changes as

¹³ As shown in Table 1, there is also little evidence of conditional mean dynamics in the differenced intraday yield data for Tokyo and New York. However, there is some evidence of conditional mean dynamics for London with a small, but statistically significant, mean yield change and a significant Q(20) statistic indicating serial correlation. Results throughout the paper are the same qualitatively when we include a constant term in the mean specification for the London hours. Furthermore, we believe the Q(20) statistic for London is a finite sample result that can be safely ignored because of its unusual pattern and p-value of 9.4%.

$$\varepsilon_{i,t} | \Omega_{i-1,t} \sim D(0, h_{i,t})$$

for $i = 1, 2, 3$, where $\Omega_{i-1,t}$ is the information set available at the start of segment i on date t , D is the distribution of $\varepsilon_{i,t}$, and

$$h_{i,t} = \omega_i + \beta_i h_{i,t-1} + \sum_{j=1}^{i-1} \alpha_{i,j} \varepsilon_{j,t}^2 + \sum_{j=1}^3 \alpha_{i,j} \varepsilon_{j,t-1}^2,$$

or equivalently,

$$h_{1,t} = \omega_1 + \beta_1 h_{1,t-1} + \alpha_{11} \varepsilon_{1,t-1}^2 + \alpha_{12} \varepsilon_{2,t-1}^2 + \alpha_{13} \varepsilon_{3,t-1}^2,$$

$$h_{2,t} = \omega_2 + \beta_2 h_{2,t-1} + \alpha_{21} \varepsilon_{1,t}^2 + \alpha_{22} \varepsilon_{2,t-1}^2 + \alpha_{23} \varepsilon_{3,t-1}^2,$$

$$h_{3,t} = \omega_3 + \beta_3 h_{3,t-1} + \alpha_{31} \varepsilon_{1,t}^2 + \alpha_{32} \varepsilon_{2,t}^2 + \alpha_{33} \varepsilon_{3,t-1}^2.$$

That is, the intramarket variance follows a standard GARCH specification with the squared out-of-market yield changes included as exogenous variables. The parameter values for each market segment are estimated using quasi-maximum likelihood methods based on the normal distribution.

Although the actual distributions of the ε_{it} 's are non-normal, as indicated by the statistics reported in Table 1, valid inference on the consistent parameter estimates is possible using Bollerslev-Wooldridge (1992) robust standard errors.

Within this modeling framework, the two hypotheses on how information is incorporated during the trading day can be tested. The heat wave hypothesis is that the volatility of yield changes within a market segment is driven by location-specific factors that do not impact volatility in the other market segments. This hypothesis therefore implies that the α_{ij} parameters equal zero for $i \neq j$. The alternative meteor shower hypothesis is that volatility is transmitted from one market segment to another, implying that the α_{ij} parameters are significantly different from zero for $i \neq j$.

As noted earlier, Treasury market volatility is substantially higher during the New York trading hours than during Tokyo or London trading hours. Furthermore, much of this volatility seems to originate with macroeconomic announcements released during New York trading hours. This evidence leads to the conjecture that if volatility spillovers do occur, they probably flow from New York to the overseas trading centers. Volatility spillovers into New York would seem to be less likely to occur due to the relative scarcity of large yield changes in the overseas markets and would seem to be harder to detect given the greater information flow during the New York trading hours. The implication is that significant out-of-market parameters, indicating the meteor shower form of volatility spillover, are more likely to be found for Tokyo and London than for New York.

B. Results

We first analyze the conditional variance of daily yield changes, defined as the 24-hour change in closing yields for each trading center. The GARCH(1,1) results, available from the authors, indicate that the GARCH form of heteroskedasticity is present in daily yield changes. The GARCH parameters and the Wald statistics with respect to the homoskedastic model are significant at the 5% level for all three series. Furthermore, in line with the existing literature on interest rates and other financial time series, the coefficient sums ($\alpha_i + \beta_i$) are only slightly less than one, indicating a high degree of volatility persistence. While the daily results show that information accumulated over the course of a trading day impacts future volatility, the source of such volatility persistence is not known. As noted by Engle *et al.* (1990), daily volatility persistence may arise from serial correlation in the arrival of location-specific news or it may arise from volatility spillovers across different trading centers within a day.

We proceed to examine the per-hour volatility of yield changes within each trading center. The estimated GARCH(1,1) results, shown in Table 3, indicate the presence of the GARCH form of heteroskedasticity in intraday yields. The GARCH parameters and the Wald statistics with respect to the homoskedastic model are significant at the 5% level for all three series. As with the daily series, the sums of the coefficients ($\alpha_i + \beta_i$) are just less than one, indicating a high degree of volatility persistence. Information accumulated over the course of a market's trading hours therefore impacts future volatility within that market.

To further examine these volatility dynamics, information accumulated during the out-of-market trading hours is incorporated into the model, as discussed earlier. As shown in Table 4, the results indicate volatility spillovers for Tokyo and London, but not for New York. For Tokyo, the coefficients on the New York and London yield changes are significant at the 5% and 10% levels, respectively, and the Wald statistic rejects the null hypothesis that these parameters are jointly equal to zero. For the London market, the coefficients on the Tokyo and New York yield changes are both significant at the 5% level and the Wald statistic is again significant. For New York, neither the Tokyo nor the London yield change coefficient is significant at the 10% level, and the Wald statistic is here insignificant. These results clearly reject the heat wave hypothesis in favor of the meteor shower hypothesis for Tokyo and London with information generated out-of-market impacting the variance of within-market yield changes. However, the heat wave hypothesis is not rejected for New York, as only information generated during New York trading hours seems to impact the variance of yield changes in New York.

Tokyo and London also differ from New York in that both show starkly different degrees of volatility persistence once the out-of-market terms are added to the variance equation. As shown in Tables 3 and 4, the estimated GARCH parameter for Tokyo drops from a very

significant 0.90 to an insignificant 0.005 in the model with out-of-market terms, and the sum of coefficients drops from 0.93 to 0.09. Thus, the GARCH effect basically disappears in the modified model, and Tokyo volatility depends solely on the previous day's yield change for Tokyo and on the yield changes since the last Tokyo close. For London, the estimated GARCH parameter falls from 0.91 to 0.62 in the model with out-of-market terms, and the sum of coefficients drops from 0.98 to 0.72. The own-market volatility persistence is therefore reduced but still present for London. In contrast, the estimated volatility parameters for New York are little changed by the addition of the out-of-market terms.

These findings for the Treasury market contrast with those for the foreign exchange market where meteor showers are transmitted from the overseas locations to New York as well as from New York to the overseas locations (see Engle *et al.* (1990); Ito, Engle, and Lin (1992); and Melvin and Peiers (1997)). Differences in information arrival across the trading locations may explain these contrasting results. As noted earlier, Treasury yield volatility is higher during New York trading hours, largely due to macroeconomic announcements made during those hours. It therefore seems reasonable that volatility spillovers emanating from New York might occur and be easily detectable, while spillovers into New York either do not occur or are not easily detectable due to the greater degree of information generated during those hours.

C. Specification and Robustness Tests

We test for asymmetries and non-linearities in the ARCH and out-of-market terms through related variance specifications. (These results are available from the authors upon request.) With respect to asymmetric influence by negative yield changes, neither TARARCH nor EGARCH specifications indicate significant differences in volatility persistence. For the out-of-market

terms, there is little evidence of asymmetric effects; yield increases (or equivalently, price declines) in London are significantly more likely to spill over into Tokyo than yield decreases (price increases), but no such asymmetry is found for any other out-of-market terms for the three trading centers.

In contrast, evidence of possible non-linearities in the ARCH and out-of-market terms is found for all three trading centers. The squared own-market volatility term ($\epsilon_{i,t-1}^4$) is significant when it is added to the basic GARCH model, although it is positive for New York and negative for Tokyo and London. This evidence suggests that the basic GARCH model is giving insufficient weight to large yield changes for New York and too much weight to large yield changes for Tokyo and London. Yield changes of a more idiosyncratic nature overseas as compared to New York may explain this difference.

When squared out-of-market volatility terms are added to the meteor showers model, both are significantly negative for Tokyo; the Tokyo term is significantly negative for London; and neither term is significant for New York. This evidence suggests that large out-of-market yield changes are given too much weight for Tokyo and London, consistent with the finding that large own-market changes are given too much weight for these trading centers. In summary, our findings indicate the possibility of non-linearities in Treasury yield volatility persistence. This is an area for future research.

We also examine the robustness of our findings across the yield curve by analyzing the transaction yields for the on-the-run two- and ten-year U.S. Treasury notes. As with the five-year note, unit root tests indicate that these series are nonstationary, and regressions on the differenced daily yield series do not indicate the presence of a conditional mean (i.e., μ and ρ are not

significantly different from zero). The GARCH form of heteroskedasticity is indicated for both daily series with strong GARCH effects and high volatility persistence, as was found for the five-year note. Similarly, the intraday yield changes for both the two- and ten-year notes demonstrate the GARCH form of heteroskedasticity with strong GARCH effects and high volatility persistence.¹⁴

Table 5 contains the estimated parameters for the meteor showers model for these two series. Consistent with the findings for the five-year note, volatility is found to spill over into Tokyo and London for the two- and ten-year note series, but not into New York. Panel A shows that two-year yield volatility for both Tokyo and London is significantly impacted by New York yield changes, and that London is also impacted by Tokyo yield changes. The Wald statistics indicate that the out-of-market terms are jointly significant. New York volatility, in contrast, is not significantly impacted by overseas yield changes. Panel B shows qualitatively similar results for ten-year yield volatility. Our characterization of intraday volatility spillovers for the five-year Treasury note therefore holds for the other Treasury notes; that is, the heat wave hypothesis is rejected in favor of the meteor shower hypothesis for both Tokyo and London and it is not rejected for New York.

¹⁴ As with the five-year note, there is some evidence of conditional mean dynamics in the differenced intraday yield series for the two- and ten-year notes. The mean intraday yield changes for the two-year note are 0.1 basis points in Tokyo (significant at the 10% level), 0.2 basis points in London (significant at the 5% level), and -0.4 basis points in New York (significant at the 5% level). None of the mean intraday yield changes for the ten-year note are significant at the 10% level. Serial correlation in intraday yield changes is indicated for the two-year note during London trading hours by a Q(20) statistic significant at the 5% level, but is not indicated for Tokyo or New York. Serial correlation in intraday yield changes for the ten-year note is indicated for Tokyo and London by Q(20) statistics significant at the 5% and 10% levels, respectively, but is not indicated for New York. Tables of these results are available from the authors upon request.

IV. Testing for Volatility Spillovers with Volume Effects

A. Heat Waves with Volume Effects

As previously discussed, the impact of news on the behavior of financial time series is generally examined by modeling the time-series dynamics of the conditional variance. However, other indicators of market activity are available which may contain additional information about volatility. Trading volume, in particular, is considered to be a good proxy for the degree of heterogeneity in traders' beliefs. We therefore introduce a lagged trading volume component into the baseline GARCH model as per Bollerslev and Domowitz (1993). The conditional variance is now specified as

$$h_{i,t} = \omega_i + \beta_i h_{i,t-1} + \alpha_i \varepsilon_{i,t-1}^2 + \phi_i V_{i,t-1},$$

where $V_{i,t-1}$ is the detrended trading volume for market i on day $t-1$.¹⁵ The volume term is analogously added to the GARCH specifications that include out-of-market effects.

Table 6 presents the parameter estimates for the heat wave model augmented with the lagged own-market trading volume for the five-year note. For both Tokyo and London, the coefficients on lagged volume are positive with the one for Tokyo significant at the 10% level and the one for London at the 5% level. These results suggest that trading volume in the overseas markets contains significant incremental information about future volatility in those markets. However, for New York, the coefficient on lagged volume is negative and insignificant, suggesting that trading volume in New York does not contain incremental information about future volatility.

¹⁵ Trading volume is detrended by removing a constant, holiday effects, and a linear trend using simple regression analysis.

Other studies find little evidence that lagged trading activity measures contain significant information about volatility. In an analysis of high-frequency exchange rates, Bollerslev and Domowitz (1993) reject the proposition that lagged trading intensity has an independent effect on returns volatility. For a sample of actively traded stocks, Lamoureux and Lastrapes (1990) report that lagged daily trading volume has little explanatory power in the variance equation. Brooks (1998) similarly finds that lagged daily trading volume does little to improve forecast accuracy of NYSE stock index volatility, while Lin and Ito (1994) find that Tokyo Stock Exchange trading volume has no power to explain S&P 500 volatility. Our finding for New York is therefore generally consistent with the literature while our finding for the overseas markets is not.

Why might trading volume contain significant information about future volatility for the overseas markets and not for New York? We conjecture that overseas trading is comprised disproportionately of speculative activity and thus more closely measures the heterogeneity in traders' beliefs than does New York trading. In contrast, a disproportionate share of New York trading may be comprised of liquidity trading, which does not reflect heterogeneous beliefs. The predominance of U.S. investors as owners of U.S. Treasury securities and the greater liquidity during New York trading hours might result in these differences in the type of trading across markets. One piece of evidence that seems to support our conjecture is the virtual absence of overseas trading in U.S. Treasury bills, which have shorter maturities and which are less commonly used for speculative trading activity than coupon securities.

B. Meteor Showers with Volume Effects

To examine the impact of trading volume on the volatility spillover results, the meteor shower models are also augmented with lagged own-market trading volume. The estimated

results are presented in Table 7. For both Tokyo and London, the heat wave hypothesis is again rejected in favor of the meteor shower hypothesis, and lagged trading volume remains significant. Volatility spillovers are therefore present in the overseas markets even after adjusting for the effect of trading volume on the conditional variance. For New York, the heat wave hypothesis is again not rejected, and lagged trading volume remains insignificant. Further, note that the volatility persistence reported in Table 4 is not greatly affected by the inclusion of the trading volume term for any of the markets.

We also estimate a model that incorporates out-of-market trading volumes in addition to own-market volume to test, for example, whether high volume days in New York tend to be followed by volatile days in Tokyo or London. For all three trading centers, both out-of-market volume terms are insignificant and Wald tests do not reject the null hypothesis that the additional terms equal zero. Volume does not seem to spill over into the volatility of other trading centers, demonstrating that while volume may have heat wave effects on volatility it does not have meteor shower effects.

As before, we examine the robustness of the trading volume results across the yield curve by analyzing two- and ten-year U.S. Treasury note yields. These supplemental results, available from the authors, are consistent with the findings for the five-year yields. Out-of-market effects are present in both the two- and ten-year yield series for Tokyo and London even after controlling for own-market trading volume. Out-of-market effects are still not significant in New York. Own-market trading volume is found to significantly impact the conditional variance for both Tokyo and London for the two-year note series, and Tokyo for the ten-year note series.

V. Conclusion

This paper examines the volatility dynamics of intraday yield changes in the U.S. Treasury market. We find that yield changes within each of the three major trading centers exhibit the GARCH form of heteroskedasticity. Furthermore, we find that yield volatility in Tokyo and London is best characterized by meteor showers, with volatility spilling into these markets from the other trading centers. In contrast, yield volatility in New York is best characterized by heat waves, as little evidence is found that volatility spills into New York from the other trading centers.

The presence of meteor showers overseas and the absence of meteor showers in New York may be explained by differences in information arrival across the trading centers. As discussed, information arrival in the U.S. Treasury market is highly concentrated during the New York trading hours and can be attributed to events that occur only during New York trading hours. Spillovers from New York into the overseas trading centers therefore seem more likely to occur and easier to detect than spillovers from the overseas trading centers into New York.

We also examine whether trading volume impacts Treasury yield volatility. We find that lagged own-market trading volume affects the conditional variance of the Tokyo and London markets, but not that of the New York market. To explain this result, we conjecture that overseas trading may be comprised of a disproportionate share of speculative trading so that overseas trading more closely measures the heterogeneity in traders' beliefs. The addition of trading volume to the conditional variance models does not qualitatively impact our basic volatility spillover results.

In conclusion, our findings indicate a rich variety of volatility dynamics in the U.S.

Treasury securities market. Additional research into the distinctive microstructure characteristics of this global financial market is needed to explain these dynamics. For example, models that directly incorporate the effects of macroeconomic announcements on Treasury yield variance have been examined by Ederington and Lee (1998), Li and Engle (1998), Jones, Lamont, and Lumsdaine (1998), and Bollerslev, Cai, and Song (1999). Further analysis incorporating such macroeconomic announcements could help ascertain the particular information arrival patterns that cause the meteor showers observed in the Treasury market.¹⁶

The availability of higher frequency data for this market also permits study of regional, time-of-day, and other periodic volatility factors, as examined for exchange rates by Baillie and Bollerslev (1990), Andersen and Bollerslev (1997, 1998), Melvin and Peiers (1997), and Melvin and Yin (1998). Volatility persistence across trading centers could be documented more precisely with such data, and the possible non-linearities in volatility persistence could be more carefully modeled and tested. Finally, higher frequency data could allow a more detailed investigation of the causes and implications of trading activity and of why such activity seems to contain information about the conditional variance for the overseas markets, but not for New York.

¹⁶ For the foreign exchange market, for example, Hogan and Melvin (1994) examine volatility spillovers after trade balance news is reported and find that persistence is positively related to the degree of heterogeneous priors about an announcement, supporting the idea that meteor showers emanate from private information and differing beliefs.

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Table 1
Descriptive Statistics

The table reports descriptive statistics for the five-year U.S. Treasury note for each of the three major trading centers for the February 24, 1992 to August 19, 1994 period. Market trading hours are approximate and assume no volatility over weekends. Yield changes are calculated as the market-to-market change in the closing transaction yield in basis points. Trading volume is measured in tens of millions of U.S. dollars. One and two asterisks denote significance at the .10 and .05 levels, respectively.

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Market trading hours	9.5	4.5	10
Yield change:			
Mean	0.0129	0.1945**	-0.2732
Variance	2.9502	2.5455	40.7998
Variance per hour	0.3111	0.5620	4.0800
Skewness ^a	-0.4790**	-0.1036	0.1993**
Kurtosis ^a	10.37**	11.27**	4.04**
Q(20)	20.71	30.72*	14.33
Trading volume:			
Mean	12.36	23.46	447.69
Mean per hour	1.30	5.19	44.77

^a Under the assumption of normality, the skewness coefficient is distributed $N(0, 6/T)$ and the coefficient of excess kurtosis is distributed $N(0, 24/T)$, where T equals the sample size.

Table 2

Largest Yield Changes for the Five-Year U.S. Treasury Note by Trading Center

The table reports the ten largest absolute yield changes in the five-year U.S. Treasury note by trading center along with the date and cited explanation for the yield change for the February 24, 1992 to August 19, 1994 period. Cited explanations are drawn from the Wall Street Journal, Bloomberg, and various wire services.

<u>Yield Change (Basis Points)</u>	<u>Date</u>	<u>Explanation^a</u>
<u>Panel A: Tokyo^b</u>		
-13.0	September 14, 1992	Bundesbank pledges to cut interest rates
7.2	May 21, 1992	WSJ reports that Fed decided against rate cut
-6.9	February 18, 1993	Clinton presents economic package to Congress
-6.9	April 12, 1993	U.S. consumer price report weaker than expected ^c
6.8	June 23, 1993	NYT reports that Fed may raise rates
6.5	December 13, 1993	Gold prices rise
6.2	October 20, 1992	Presidential debate increases likelihood of Clinton win
6.0	June 27, 1994	Dollar falls against yen
-5.5	October 12, 1992	Greenspan says that monetary policy is not on hold
5.4	August 1, 1994	Dollar falls against yen
-5.1	June 6, 1994	NYT reports that Fed unlikely to raise rates
<u>Panel B: London</u>		
-11.9	May 10, 1994	Dollar rises
9.1	March 9, 1993	Clinton plans to spur bank lending (prior trading day)
8.7	October 9, 1992	FT reports that Fed will not cut rates
6.4	June 20, 1994	European bond prices fall
-6.0	October 21, 1992	European central banks cut interest rates
5.3	April 11, 1994	Dollar falls against yen
5.0	April 15, 1994	NYT reports that Fed intends to raise rates
4.9	November 30, 1993	WP reports that tighter monetary policy possible
-4.8	March 28, 1994	OPEC ministers fail to agree to production cuts
-4.7	November 4, 1992	Clinton elected president
4.7	July 17, 1992	Clinton widens lead in polls

Panel C: New York

25.4	May 6, 1994	Strong employment report released
-23.5	July 2, 1992	Weak employment report released, Fed cuts rates
22.7	April 18, 1994	Fed raises rates
21.7	April 1, 1994	Strong employment report released
-20.6	July 29, 1994	Weaker-than-expected GDP report released
19.5	April 4, 1994	Strong employment report released (prior trading day)
-18.5	January 7, 1994	Weaker-than-expected employment report released
18.4	April 28, 1994	Inflation measures in GDP report increase
18.2	August 5, 1994	Strong employment report released
-18.0	September 4, 1992	Weak employment report released, Fed cuts rates
-18.0	May 17, 1994	Fed raises rates

^a *FT = Financial Times, NYT = New York Times, WP = Washington Post, WSJ = Wall Street Journal.*

^b The list excludes January 4, 1993, when the Tokyo yield change is calculated to be 5.4 basis points, as the dataset is missing the previous day of trading (December 31, 1992) when most of this yield change took place.

^c This is the first chance the market had to respond to the report since it was released on a non-trading day (Good Friday) in New York.

Table 3
Heat Wave Model Estimates

The table reports estimates of the GARCH(1,1) model using market-to-market yield changes in the five-year U.S. Treasury note for the three major trading centers for the February 24, 1992 to August 19, 1994 period. Model coefficients are reported with Bollerslev-Wooldridge standard errors in parentheses. One and two asterisks denote significance at the .10 and .05 levels, respectively.

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Constant _t	0.0224 (0.0195)	0.0142 (0.0149)	0.0544 (0.0592)
$g^2_{i,t-1}$	0.0250* (0.0151)	0.0655** (0.0285)	0.0260 (0.0173)
$h_{i,t-1}$	0.9045** (0.0736)	0.9143** (0.0517)	0.9606** (0.0284)
L	-525.15	-696.90	-1337.02
Wald ^a	297.01**	1315.40**	5983.56**

^a Wald test of the null hypothesis that the GARCH parameters jointly equal zero.

Table 4
Meteor Shower Model Estimates

The table reports estimates of the GARCH(1,1) model with out-of-market effects for the five-year U.S. Treasury note for the three major trading centers for the February 24, 1992 to August 19, 1994 period. Model coefficients are reported with Bollerslev-Wooldridge standard errors in parentheses. One and two asterisks denote significance at the .10 and .05 levels, respectively.

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Constant _t	0.1371** (0.0426)	0.0165 (0.0214)	0.0940 (0.0688)
$g^2_{i,t-1}$	0.0841** (0.0419)	0.0970** (0.0470)	0.0248 (0.0168)
$h_{i,t-1}$	0.0050 (0.0885)	0.6212** (0.0860)	0.9464** (0.0279)
$g^2_{LN,t}$	---	---	0.0406 (0.0533)
$g^2_{TK,t}$	---	0.1380** (0.0515)	-0.0107 (0.0860)
$g^2_{NY,t-1}$	0.0346** (0.0129)	0.0240** (0.0102)	---
$g^2_{LN,t-1}$	0.0511* (0.0297)	---	---
L	-490.75	-647.78	-1335.10
Wald ^a	15.27**	10.72**	0.68

^a Wald test of the null hypothesis that the parameters on the two out-of-market effects jointly equal zero.

Table 5

Meteor Shower Model Estimates for the Two-and Ten-Year Notes

The table reports estimates of the GARCH(1,1) model with out-of-market effects for the two- and ten-year U.S. Treasury notes for the three major trading centers for the February 24, 1992 to August 19, 1994 period. Model coefficients are reported with Bollerslev-Wooldridge standard errors in parentheses. One and two asterisks denote significance at the .10 and .05 levels, respectively.

Panel A: Two-Year U.S. Treasury Note

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Constant _t	0.0040 (0.0074)	0.0018 (0.0118)	0.0373 (0.0480)
$g^2_{i,t-1}$	0.0069 (0.0140)	0.0482** (0.0229)	0.0135 (0.0144)
$h_{i,t-1}$	0.8727** (0.0694)	0.7836** (0.0838)	0.9699** (0.0273)
$g^2_{LN,t}$	---	---	0.0107 (0.0383)
$g^2_{TK,t}$	---	0.1020* (0.0620)	0.0491 (0.0868)
$g^2_{NY,t-1}$	0.0070** (0.0033)	0.0133** (0.0063)	---
$g^2_{LN,t-1}$	0.0164 (0.0186)	---	---
L	-490.28	-608.93	-1302.04
Wald ^a	4.67*	5.16*	1.08

Panel B: Ten-Year U.S. Treasury Note

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Constant _t	0.1160* (0.0611)	0.0489* (0.0270)	0.0882 (0.0682)
$g^2_{i,t-1}$	0.0820* (0.0476)	0.1418** (0.0651)	0.0305* (0.0179)
$h_{i,t-1}$	0.0880 (0.2013)	0.4099** (0.0960)	0.9297** (0.0320)
$g^2_{LN,t}$	---	---	0.1186 (0.0943)
$g^2_{TK,t}$	---	0.2480** (0.0875)	-0.0273 (0.1168)
$g^2_{NY,t-1}$	0.0163** (0.0075)	0.0268** (0.0094)	---
$g^2_{LN,t-1}$	0.0296 (0.0275)	---	---
L	-394.42	-568.79	-1271.79
Wald ^a	5.28*	19.13**	1.63

^a Wald test of the null hypothesis that the parameters on the two out-of-market effects jointly equal zero.

Table 6
Heat Wave with Trading Volume Model Estimates

The table reports estimates of the GARCH(1,1) model with detrended own-market trading volume for the five-year U.S. Treasury note for the three major trading centers for the February 24, 1992 to August 19, 1994 period. Model coefficients are reported with Bollerslev-Wooldridge standard errors in parentheses. One and two asterisks denote significance at the .10 and .05 levels, respectively.

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Constant _t	0.3430** (0.1037)	0.0331** (0.0161)	0.0505 (0.0458)
$g^2_{i,t-1}$	0.0259 (0.0336)	0.0370** (0.0144)	0.0335* (0.0194)
$h_{i,t-1}$	-0.1337 (0.2493)	0.9053** (0.0446)	0.9540** (0.0259)
$V_{i,t-1}$	0.0993* (0.0515)	0.0160** (0.0022)	-0.0028 (0.0030)
L	-515.19	-675.55	-1334.44
Wald ^a	3.72*	51.70**	0.88

^a Wald test of the null hypothesis that the parameter on trading volume equals zero.

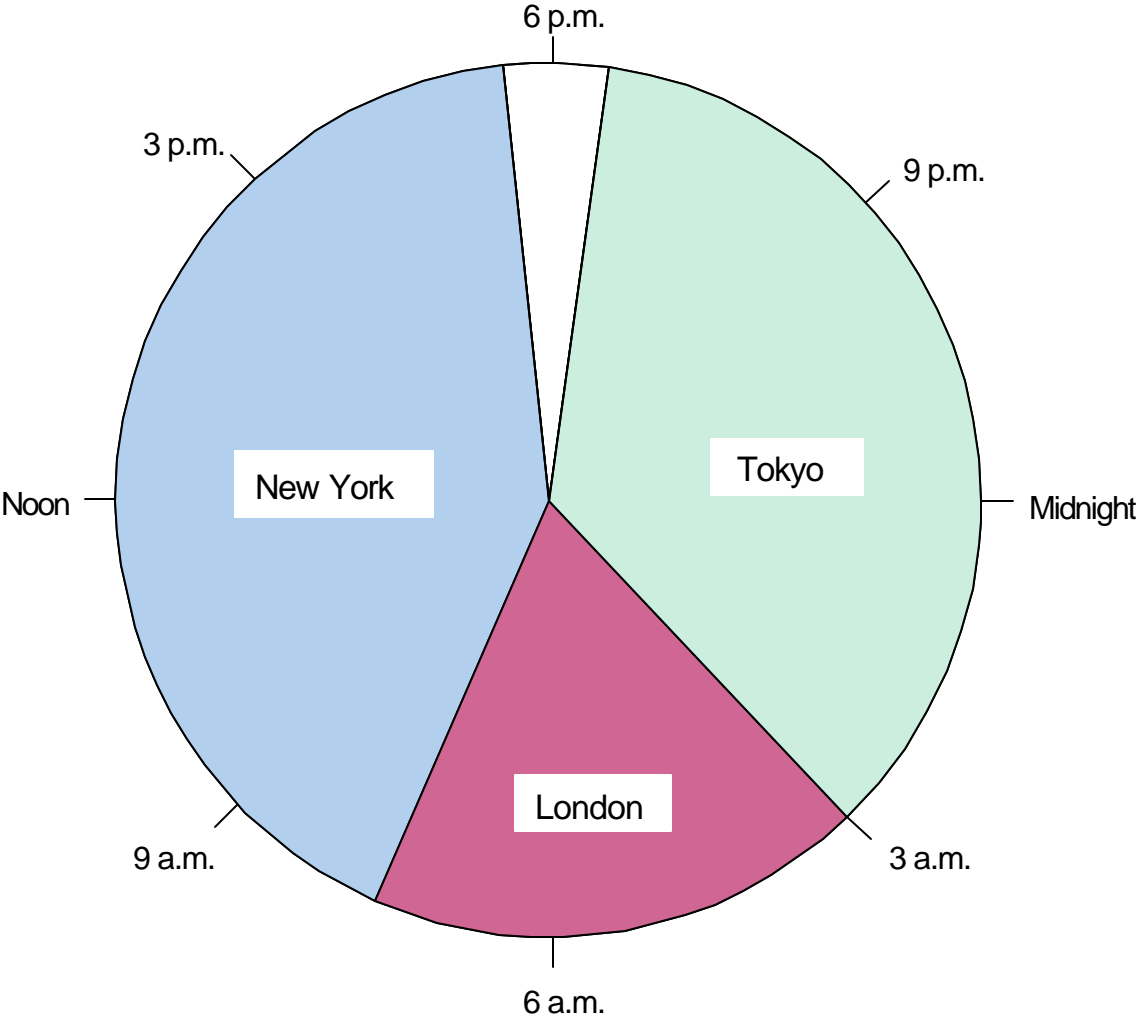
Table 7
Meteor Shower with Trading Volume Model Estimates

The table reports estimates of the GARCH(1,1) model with out-of-market effects and detrended own-market trading volume for the five-year U.S. Treasury note for the three major trading centers for the February 24, 1992 to August 19, 1994 period. Model coefficients are reported with Bollerslev-Wooldridge standard errors in parentheses. One and two asterisks denote significance at the .10 and .05 levels, respectively.

	<u>Tokyo</u>	<u>London</u>	<u>New York</u>
Constant _t	0.1779** (0.0550)	0.0163 (0.0127)	0.0751 (0.0574)
$g^2_{i,t-1}$	0.0377 (0.0360)	0.0241 (0.0205)	0.0288 (0.0192)
$h_{i,t-1}$	0.0043 (0.1176)	0.7809** (0.0591)	0.9465** (0.0277)
$g^2_{LN,t}$	---	---	0.0506 (0.0562)
$g^2_{TK,t}$	---	0.0899** (0.0369)	-0.0173 (0.0912)
$g^2_{NY,t-1}$	0.0243** (0.0084)	0.0143* (0.0087)	---
$g^2_{LN,t-1}$	0.0431 (0.0287)	---	---
$V_{i,t-1}$	0.0682* (0.0355)	0.0131** (0.0021)	-0.0032 (0.0034)
L	-486.12	-635.79	-1334.14
Wald ^a	3.70*	38.25**	0.88

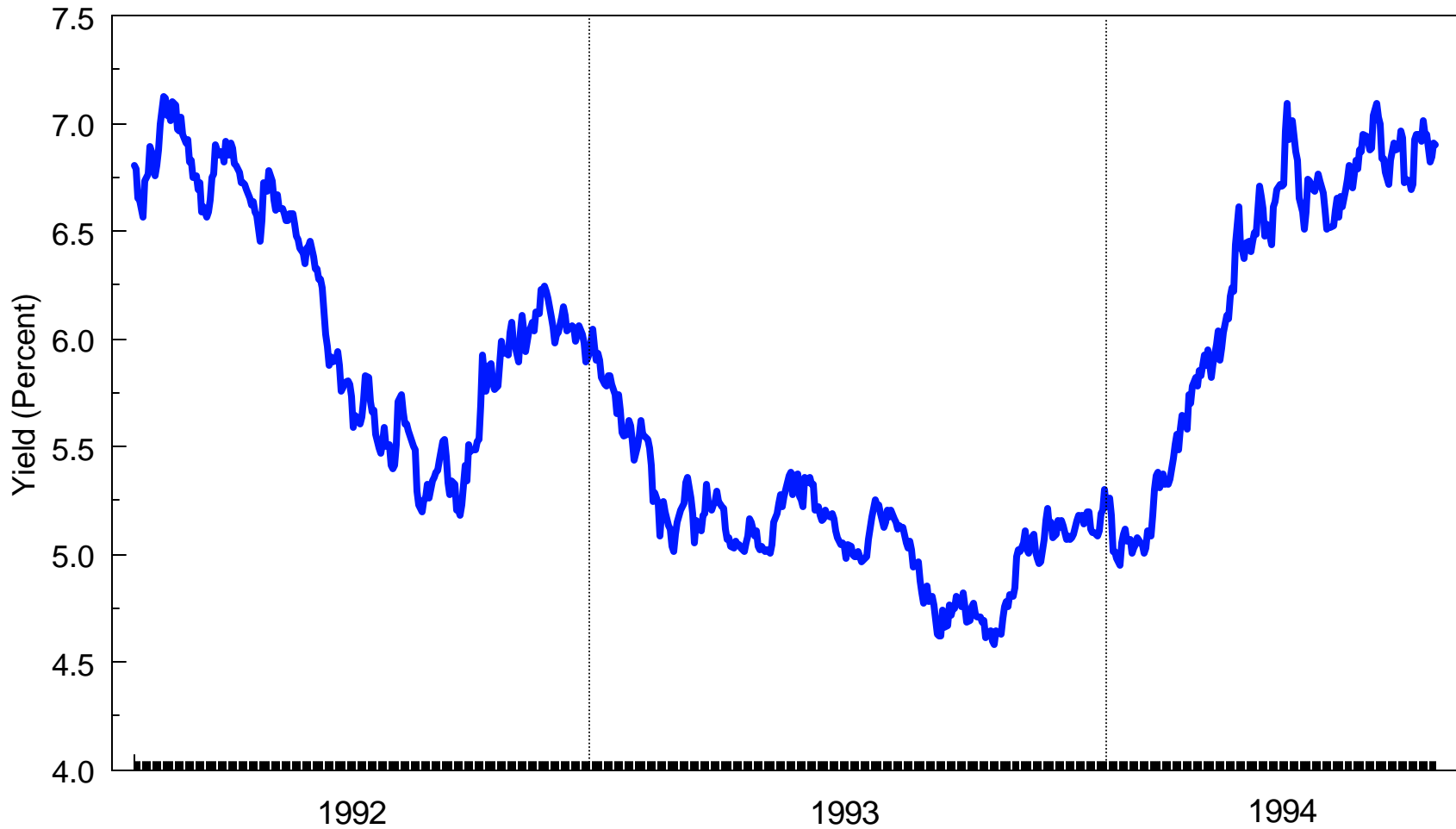
^a Wald test of the null hypothesis that the parameters on the two out-of-market effects jointly equal zero.

Figure 1
Trading Times for U.S. Treasury Securities



Notes: The figure shows the breakdown by location of interdealer trading over the global trading day. Crossover times are approximate because interdealer trading occurs over the counter and may be initiated from anywhere. All times are New York standard time.

Figure 2
Five-Year U.S. Treasury Note Yield



Note: The figure plots the daily closing New York transaction yield for the five-year U.S. Treasury note for the February 24, 1992 to August 19, 1994 period.