Discussion Papers In Economics And Business

Market Efficiency and International Linkage of Stock Prices: An Analysis with High Frequency Data

Yoshiro Tsutsui
Kenjiro Hirayama

Discussion Paper 03-04-Rev.

Graduate School of Economics and
Osaka School of International Public Policy (OSIPP)
Osaka University, Toyonaka, Osaka 560-0043, JAPAN

Market Efficiency and International Linkage of Stock Prices: An Analysis with High Frequency Data

Yoshiro Tsutsui
Kenjiro Hirayama

Discussion Paper 03-04-Rev.

October 2004

この研究は「大学院経済学研究科・経済学部記念事業」
基金より援助を受けた、記して感謝する。

Graduate School of Economics and
Osaka School of International Public Policy (OSIPP)
Osaka University, Toyonaka, Osaka 560-0043, JAPAN

Market Efficiency and International Linkage of Stock Prices:

An Analysis with High-Frequency Data*

Yoshiro Tsutsui
Osaka University

Kenjiro Hirayama
Kwansei Gakuin University

Abstract

This paper uses one-minute returns on the TOPIX and S&P500 to examine the efficiency of the Tokyo and New York Stock Exchanges. Our major finding is that Tokyo completes reactions to New York within six minutes, but New York reacts within fourteen minutes. Dividing the sample period into three subperiods, we found that the efficiency has improved and the magnitude of reaction has become larger over the period in both markets. The magnitude of response in New York to a fall in Tokyo is roughly double that of a rise.

JEL Classification Numbers: G14, G15, F36
Keywords: international linkage, stock prices, market efficiency, high frequency data

Correspondence:

Yoshiro Tsutsui
Institute of Social and Economic Research
Osaka University
6-1 Mihogaoka, Ibaraki
567-0047 Japan
Phone: +81-6-6879-8560
Fax: +81-6-6878-2766
e-mail: tsutsui@econ.osaka-u.ac.jp

Kenjiro Hirayama
School of Economics
Kwansei Gakuin University
Uegahara, Nishinomiya-shi
662-8051 Japan
Phone: +81-798-54-6438
Fax: +81-798-54-6438
e-mail: hiraken@kwansei.ac.jp

* An earlier version of this paper was presented at MEW (the Monetary Economics Workshop), the 11th annual convention of the Nippon Finance Association, and the Spring Meeting of Japan Economic Association. The authors are grateful for helpful comments by Masayuki Ikeda, Hideaki Kato, Toshio Serita, and participants at the workshop.

1. Introduction

Stock prices of major economies are well known to be interdependent, and there is an extensive literature on international stock price linkage (Eun and Shim (1989), Jeon and von Furstenberg (1990), Mathur and Subrahmanyam (1990), Jeon and Chiang (1991), Chan *et al*. (1992), Kasa (1992), Corhay *et al*. (1993), Blackman *et al*. (1994), Chung and Liu (1994), Choudhry (1994, 1997), and Hirayama and Tsutsui (1998a, b)), including a few research papers which investigate the possible causes of the linkage (Tsutsui (2002), Tsutsui and Hirayama (2004b, c)). One of the findings in this literature is that a country's stock prices tend to advance when a neighboring market, closing just before that of the country's market, has advanced (Tsutsui and Hirayama 2004a).

Therefore, one can predict the course of the stock price index of the Tokyo stock market, such as the TOPIX or the Nikkei 225, by observing whether the stock price indices of the New York stock market, such as the S&P500 and the New York Dow Jones Industrial Average (henceforth known as NYDJ), have advanced or declined. This predictability might seem to contradict the market efficiency hypothesis, but such is not the case. When the New York Stock Exchange (NYSE) is open for trading, the Tokyo Stock Exchange (TSE) is closed due to time differences. Consequently, one must wait for the opening of the TSE to execute transactions based on the new information from New York. If the Tokyo stock market is efficient, the TOPIX reacts fully to the information of the S&P500 on the previous day at the opening but is not influenced thereafter.

Using daily opening and closing values, Tsutsui (2002) found that the Nikkei 225 reacts to a large change (over 1.5%) of NYDJ by the closing time of the next day, and the Nikkei 225 does not show a significant change beyond the following day. Thus, the Tokyo stock market is efficient over the daily time span.

Although the studies above use daily observations at best, there is a body of literature that utilizes observations of high frequency.[1] The markets for foreign exchange and interest rate futures seem to react extremely rapidly to macroeconomic news announcements, e.g., within forty seconds according to Ederington and Lee (1995) and Almeida *et al*. (1998). However, equity markets respond more slowly to earnings and dividend announcements, requiring ten to fifteen minutes (Patell and Wolfson (1984)). The response of the S&P500 index to unexpected changes in the money supply and Consumer Price Index (CPI) is completed within one hour (Jain (1988)). In this paper, we will employ one-minute returns on the TOPIX and the S&P500 to analyze the speed of reactions of each stock exchange to the other.

The only work thus far, to our knowledge, using intraday data in a study of the price linkage between the U.S. and Japanese stock markets is that of Becker *et al*. (1992). They used hourly data for the S&P500 and Nikkei 225 Indices from October 5, 1985 to December 31, 1989. They calculated the correlations between hourly returns of one country with the other country's daily

[1]For an overall introduction to high-frequency finance, see Dacorogna *et al*. (2001). Goodhart and O'Hara (1997) is also a good review and companion papers in the same *Journal of Empirical Finance*, vol. 4, no. 2-3 are research results with high-frequency data.

return of the previous day.[2] They found that the effect of the previous day's Nikkei return on the subsequent S&P500 returns is absorbed within the first half hour after opening in New York, while the effect of the previous day's S&P500 return on the subsequent Nikkei returns is absorbed within the first hour of trading in Tokyo, and that the effect of the lagged S&P500 returns on the subsequent Nikkei returns is larger than the reverse effect.

Thus, the stock markets in Tokyo and New York seem to absorb the effects from the other stock exchange rather rapidly. However, due to the hourly observations that they used we cannot infer how speedily the effects are absorbed. In other words, we cannot compare the relative efficiency of the two stock markets.

This paper uses high-frequency data to examine the market efficiency of the Tokyo and New York stock markets. We obtained the tick data for the S&P500 from Tickdata.com and the TOPIX data at one-minute intervals from the Tokyo Stock Exchange.[3] Our data started earlier, but to avoid the extreme effects of Black Monday, we discarded data before December 1987. The last day for our sample was November 27, 2003. By comparing how quickly each stock market reacts to the other's movements, we can infer which market is more efficient in absorbing the effects of the other. Further, since our sample period is considerably longer than that used in Becker *et al*. (1992), we can also examine whether there was a change in this efficiency during the sample period.

---

[2] Since the New York Stock Exchange opens at 09:30 EST, the first US return of the day is a half-hour return from 09:30 to 10:00.

[3] The TOPIX is a capitalization-weighted index of all the stocks listed on the Tokyo Stock Exchange.

2. Intraday patterns of one-minute stock returns

2.1 Intraday patterns of TOPIX returns

We obtained the TOPIX data at one-minute intervals from 09:01 to 15:00 JST (Japan Standard Time) from May 23, 1987 to November 27, 2003 from the Tokyo Stock Exchange. There was a two-hour lunch break between 11:00 and 13:00 until April 26, 1991 and a 90 minute lunch break between 11:00 and 12:30 after April 30, 1991. Although the actual starting date of our dataset is May 23, 1987, we deleted observations up to the end of 1987 in order to avoid overwhelming influence of the Black Monday. One-minute returns of the TOPIX are computed as:

$$RJhhmm_t = \frac{TOPIX\ at\ hhmm - TOPIX\ at\ hhmm-1}{TOPIX\ at\ hhmm-1} \times 100, \qquad (1)$$

where *hhmm* is a four-digit number denoting the hours and minutes in Japan Standard Time and *hhmm*–1 refers to the time one minute before *hhmm*. It takes on values from 0901 to 1100 for the morning session and from 1231 to 1500 for the afternoon session.[4] The notation, 1000–1, means 0959, but 0901–1 refers to 1500 of the previous day. Therefore, note that *RJ0901* is actually an overnight return from the previous day's close at 15:00. Likewise, 1231–1 is actually 1100, because there is a lunch break. Hence, *RJ1231* is a 90-minute return from 11:00 to 12:31.

These TOPIX returns, *RJ0901*, …, *RJ1500*, are averaged across days during the

[4] Due to a longer lunch break, *hhmm* starts at 1301 and ends at 1500 for the afternoon session until April

sixteen-year period (January 1988 to November 2003), and these means are plotted in Figure 1 along with 95% confidence bands based on the null of a zero mean. We observe the following five characteristics of intraday one-minute stock returns in Tokyo:

1) The first four minutes immediately following a day's opening exhibit significantly positive returns.

2) There are significantly positive returns for about six minutes before a day's closing.

3) There are significantly negative returns for about ten minutes after the opening (12:31) of the afternoon session.

4) One-minute returns tend to be negative after the first eight minutes of the day's opening. Out of 52 one-minute returns from *RJ0909* to *RJ1000*, there are 25 significantly negative values at a 95% level.

5) Most returns other than the above are statistically not different from zero during the day. There are only six cases of significant non-zero means for 60 one-minute returns during 10:01 and 11:00. For the interval between 12:41 and 14:54, there are 11 such means out of 134 one-minute returns.

=================

Figure 1 is about here

=================

Table I lists summary statistics of selected daily TOPIX returns. Normality tests are not shown here, since the Jarque–Bera measure indicates overwhelming rejection of normality in

26, 1991.

every variable. The means exhibit the tendencies pointed out above. *RJ0901* is actually the daily close-to-open overnight return, the mean of which is positive, whereas the daily open-to-close return (*RJOC*) is negative. There is a tendency for the TOPIX to rise during the night but to decline during the trading hours. The morning return between 09:01 and 12:31 (*RJMN*) tends to be negative, but the afternoon return between 12:31 and 15:00 (*RJAN*) positive. The volatility as measured by the standard deviation is higher at the opening of either the morning or the afternoon session and at the closing of the day. The serial correlation measured by the Ljung–Box statistic is also significant during these minutes and daily returns such as *RJCC*.

================
Table I is about here
================

Autocorrelation coefficients (not displayed here) of these one-minute returns exhibit a rapid decay, but there is an apparent periodicity at five-minute intervals. After some experimentation, we found that this pattern of high autocorrelations at five-minute intervals appears after April 1997.[5] Further probes revealed that this pattern is caused by data between 09:00 and 10:00 and that a very high standard deviation is observed at 09:01, 09:06, 09:11, and 09:16. Volatile returns in these minutes are characterized by especially low negative values (large in absolute value). These returns are also characterized by very high autocorrelation with returns at the same minute of the previous day. We believe that this anomaly is caused by

[5] However, it was weak during April 1997 and March 1998.

special quotes, which were introduced into the system in August 1998. These quotes are updated every five minutes, and are announced whenever the next equilibrium price exceeds a predetermined band. The quotes are set at the ceiling or the floor of this band and execution of orders is suspended temporarily. The announcement is designed to alert market participants to a substantial change in price and to encourage them to place orders to exploit the new information. When a special quote fails to induce the price to stay within the band, the band is doubled and a new special quote is announced after five minutes. Thus, the purpose of these quotes is to smooth out the price path. Since they are updated at five-minute intervals, they are likely to produce autocorrelation at this frequency. In addition, the overwhelming majority of special quotes are announced at the opening.[6]

Using five-minute returns of the Nikkei 225 Index, Andersen *et al*. (2000) examined their volatility during the period from 1994 to 1997. The mean returns averaged across days are plotted in their Figure 1A and these conform to points 2, 3, and 5 above. However, the opening of the morning session exhibits a negative return, which is inconsistent with point 1 above. This may be explained by their use of a linear filter to eliminate first-order autocorrelation.

2.2 Why do positive returns prevail at opening and closing of daily trading?

As shown above, the TOPIX exhibits significantly large positive returns at the opening and

[6] The Volume Weighted Average Price (VWAP) transactions are also a candidate for the cause of this anomaly, since they were introduced in November 1997 and securities companies that undertake them are said to place buy and sell orders only periodically at five-minute intervals to minimize impacts on the market price. However, VWAP transactions are conducted throughout the day, which therefore

closing of daily trading. To investigate possible causes, we present correlation coefficients between the last 8-min. return (*RJ08M1500*) and other various returns in Table II. *RJ08M1500* has a weak positive correlation with the first 14-min. return of the day (*RJ14M0915*), but has a weak negative correlation with the subsequent close-to-open return ($RJ0901_{+1}$) and the first 14-min. return the following day ($RJ14M0915_{+1}$). Thus, positive returns at the opening and at the closing do not seem to be linked. However, a significantly high positive correlation exists between *RJ0901* and *RJ14M0915*, which indicates the following two possibilities. One is that high *RJ0901* causes high *RJ14M0915*, in other words, there is a strong serial correlation in these minutes. The other is that these positive returns at the opening and at the subsequent times are produced by the same cause, i.e., the impact of the New York market. In the next section, we specify a model (equation (3)) that incorporates both the possibilities. Especially, we analyze the effect of close-to-close returns of the New York market on the previous day.

================
Table II is about here
================

In a study of daytime (i.e., during trading hours) and overnight (i.e., during nontrading hours) returns in Tokyo, Tsutsui (2003) examines how the opening price reacts to a substantial rise or fall of the preceding closing price in Japan. He concludes that if the previous trading hours have reflected bearish trading, then the bearish sentiment will not be taken over to opening time, as opposed to when the previous trading hours reflect a more bullish attitude.

---

contradicts the fact that this five-minute periodicity appears only during 9:00-10:00.

Thus, the reaction is asymmetric depending on a fall or rise of the closing price. He also argues that a possible buying strategy of securities companies at the opening may be the cause of the rise during nontrading hours. These companies obviously benefit from higher stock prices which generate greater brokerage fees. This is an interesting view, but still needs evidence to support it. In addition, as positive returns at the opening are also recognized for S&P500 as shown in subsection I.D, the complete explanation should apply to both countries.

Regarding the tendency for the TOPIX to rise toward the end of the day, we have no explanation at all. Because the S&P500 does not show a similar rise at closing, the cause should be specific to Japan. Thus, the batch process (called *itayose* [7]) may be the cause for the positive return, but it requires additional explanation since the opening price of the afternoon session, which is also formed by the batch process, exhibits a significant negative return. It is left as a puzzle for future research.

2.3 Why does the TOPIX decline at the opening of the afternoon session?

What about the apparent tendency of stock prices to decline at the opening of the afternoon session (point 3 above)? Our conjecture is that investors give a second thought to rising prices at the opening. This may also be behind the tendency of declining prices during 09:15 and 10:00 (point 4 above). Correlation coefficients between the overnight return

[7] Opening and closing prices of the morning and afternoon session of the Tokyo Stock Exchange are formed by a batch process, called *itayose*, while other trades during the day are carried out by continuous trading, called *zaraba*. Amihud and Mendelson (1991) analyze *itayose* system and argue that this difference in the two price formation processes, *itayose* and *zaraba*, may produce differences in

(*RJ0901*), the return during the lunch break (*RJ1231*), and the 45-min. return from 09:15 to 10:00 (denoted by *RJ45M1000*) are presented in Table III. *RJ0901* is negatively correlated with both *RJ1231* and *RJ45M1000*, which seems to support our view that advances at the opening are corrected afterwards.[8]

================
Table III is about here
================

Since correlation coefficients measure pair-wise relationships only, we also ran some regressions to explain the negative return at the opening of the afternoon session. We regressed the over-lunch return (*RJ1231*) on a constant, the overnight return (*RJ0901*), five one-minute returns immediately preceding the lunch break, and the dependent variable lagged by one day.[9] The result is shown under equation (i) in Table IV. The coefficient on *RJ0901* is negative at a 6% significance level and the *RJ1100* variable has also a highly significantly negative effect on the dependent variable. *RJ1231* lagged one day has a significantly positive effect. Overall this regression gives an adequate explanation of *RJ1231*.

================
Table IV is about here
================

Before introducing the 45-min. return, *RJ45M1000*, to the regression for *RJ1231*, let us consider what effects it may have on *RJ1231*. There are two views. First, suppose that the size of correction to an over-reaction at 09:01 is determined first and that it is divided into

---

prices and trading volumes.

[8] There is, however, sensitivity to the choice of duration. The 50-min. return from 09:10 to 10:00 (*RJ50M1000*) is positively correlated with *RJ0901*.

RJ45M1000 and *RJ1231*. Then, if sufficient second thought is given during the 45-min. interval up to 10:00, the extent of corrective reaction at 12:31 must be small, making the coefficient on *RJ45M1000* negative. Second, suppose that the size of correction is not immediately known but is gradually revealed during the actual trading session. Then, if a relatively large adjustment occurred in *RJ45M1000*, it would lead to a further adjustment after lunch. In this instance, the coefficient on *RJ45M1000* in a regression for *RJ1231* tends to be significantly positive, indicating a further, strengthened correction after lunch. In any case, the lunch break gives investors further time to reconsider the excessive rise at the opening of the day.

Equation (ii) of Table IV is the result of regressing *RJ1231* on a constant, the overnight return at the opening (*RJ0901*), and the 45-min. return to 10:00 (*RJ45M1000*). The coefficient on *RJ0901* is significantly negative at a 7% level and that on *RJ45M1000* is positive at a 0.3% significance level. This result implies the second view above is appropriate.

We added five lagged one-minute returns and one-day lag of the dependent variable to the right-hand side and the basic result is the same in this equation (iii) of Table IV. These results imply that the mean negative return at the opening of the afternoon session is a reaction to the mean positive return at the opening of the morning session. Having lunch gives investors reflective time to digest the excessive rise at the day's opening.

---

[9] See the next section for the details of this regression specification.

2.4 Intraday patterns of S&P500 returns

For the U.S. stock prices we obtained tick data on S&P500 from January 2, 1987 to November 27, 2003. As noted above, we discard observations up to the end of 1987. We compute one-minute returns of S&P500 as:

$$RUhhmm_t = \frac{S\&P500\ at\ hhmm - S\&P500\ at\ hhmm-1}{S\&P500\ at\ hhmm-1} \times 100 . \qquad (2)$$

Since the New York Stock Exchange opens at 09:30 and closes at 16:00, *hhmm* takes on values from 0931 to 1600. Unlike Tokyo, the NYSE has no lunch break and trades shares continuously for six and a half hours every day. The time difference between Tokyo and New York is fourteen hours (thirteen hours during the Daylight Saving Time period). Expressed in Greenwich Mean Time, the trading hours are from 0:00 to 6:00 GMT in Tokyo and from 14:30 to 21:00 GMT in New York (see Figure 2). Thus, the two markets are never synchronously open.

=================
Figure 2 is about here
=================

Mean one-minute returns of S&P500 are plotted in Figure 3 along with 95% confidence bands based on the null of a zero mean. We observe the following features from this Figure similar to those of TOPIX one-minute returns:

1) The first seven minutes after the day's opening tend to exhibit significantly positive returns. However, their absolute magnitude is smaller than that of Tokyo.

2) The last four minutes before the day's closing are also significantly positive, but their

absolute magnitude is smaller than in Tokyo or the first few minutes after opening.

3) Some of the returns tend to be *negative* between 9:51 and 10:13. Out of 23 one-minute returns during this interval, nine are significantly negative.

4) Except for these intervals noted above, most of the mean returns are statistically not different from zero. Out of 343 one-minute returns during 10:13 and 15:56, only 28 are significant at a 5% level.

================

Figure 3 is about here

================

The correlation coefficient between the overnight return at the opening (*RU0931*) and the 45-min. return from 09:45 to 10:30 is –0.0401 with a *t*-statistic of 2.54, the *p*-value of which is 1.1%, indicating a significantly negative correlation. As in Tokyo, this may also imply that the investors in the NYSE give a second thought to the rise at and immediately after the day's opening.

Table V gives summary statistics for these and other daily returns.[10] Again the normality is overwhelmingly rejected, thus not shown therein. Unlike the TOPIX, the S&P500 tends to rise during the trading hours (significantly positive open-to-close return, *RUOC*). Most of this rise

[10] There is a slight discrepancy in the data for S&P500. The S&P500 price level at 16:00 is not precisely equal to the closing value as reported by the TickWrite, software provided by the data vendor (TickData) to retrieve data points at desired frequency. It turns out that the original tick data contain values at a few minutes after 16:00. The last value for the day is reported as the closing price. A similar discrepancy occurs with the opening price. If two or more data points exist between 09:30 and 09:31, the last value is reported as the price at 09:31, but the very first value is reported as the opening price on a daily frequency. In empirical analyses below, the daily close-to-close or open-to-close returns (*RUCC* and *RUOC*) and the like are based on true opening and closing values. However, the difference is extremely small and the results are almost identical even if the values at 09:31 and 16:00 are treated as the opening and closing prices.

during the daytime occurs in the afternoon (significantly positive afternoon return from 13:01 to 16:00, *RUAN*). The volatility is high when the market opens, as indicated by a high standard deviation of *RU0931*, but it declines gradually over time. There is no increase in volatility toward the end of the day. Serial correlation is also present at and immediately following the opening or for daily returns.

================
Table V is about here
================

3. How quickly does one market react to the other?

3.1 Correlation coefficients

Since it is well known that the two stock markets affect each other, our primary focus here is on determining how rapidly this influence is absorbed after the opening of a market. As a preliminary investigation, we compute correlation coefficients between the previous day's daily return in New York and each one-minute return in Tokyo. We denote by *RUCC* the daily close-to-close return in New York on the previous day.[11]

These correlation coefficients are displayed with 95% confidence bands derived from the null of zero correlation in Figure 4. They are positive and of no small magnitude until 09:21. Namely, correlations with preceding $RUCC_{t-1}$ persist for about twenty minutes after the opening of the TSE. There are spikes at 09:01, 09:06, 09:11, 09:16 and 09:21, but they

[11] Although this daily close-to-close return in New York is recorded on the previous calendar date, it is observed only three hours before the opening of the Tokyo market since 16:00 in New York is 06:00 the next day in Tokyo (see Figure 2).

disappear when the sample period is restricted to before March 1997. Thus, these spikes are most likely related to five-minute periodicity in autocorrelation coefficients mentioned in Section I.A. After 09:21 correlation coefficients are roughly close to zero, except at and for several minutes after 12:31 (opening of the afternoon session) when they are significantly negative. Thus far, the pattern is similar to that of mean returns of Figure 1. A notable difference exists toward the end of the day. While mean returns indicate that stock prices rise toward the end of the day, they are totally uncorrelated with previous day's movements in New York.

================

Figure 4 is about here

================

Next we reverse the direction and compute correlation coefficients between each one-minute S&P500 return and the preceding daily close-to-close return observed in Tokyo (*RJCC*). In this instance, the daily return in Tokyo is the one observed on the same calendar date as New York because the close of Tokyo at 15:00 JST is 01:00 EST (Eastern Standard Time) in New York and the NYSE opens its trading eight and a half hours later on the same day (see Figure 2). These coefficients are plotted in Figure 5. There are significantly positive correlations in the first fifteen minutes (until 09:45), but their magnitude is far less than that of Tokyo. After the initial responses, coefficients seem to be random around zero.

================

Figure 5 is about here

================

In both Tokyo and New York, the responses to the other's daily movements dissipate within the first fifteen to twenty minutes of daily trades. Thus, information from the other market seems to be rather quickly absorbed and this may indicate efficiency of the two stock markets.

3.2 Regression analysis: effect of New York on Tokyo

The main purpose of this paper is to determine how the other market affects one-minute returns of the day and especially how rapidly the effects are dissipated at the opening of daily trades. In order to investigate this effect, regression analysis taking into account other effects on the stock returns may be more appropriate than computing simple correlation coefficients.

One-minute returns averaged across days as plotted in Figures 1 and 3 exhibit non–random behavior immediately after the opening and toward the closing of the day. In Tokyo, the returns are significantly negative at and after the opening of the afternoon session. This pattern may be evidence of serial correlation that persists for a few minutes. In addition, as discussed above, returns are correlated with the same values of the previous day, indicating a daily periodicity. A model of this influence should take into account both short-run serial correlation and daily periodicity.

Thus, our model of one-minute TOPIX returns is specified as follows:

$$RJhhmm_t = \alpha_{hhmm} + \sum_{i=1}^{5} \beta_{hhmm}^{i} RJ(hhmm-i)_t + \gamma_{hhmm} RJhhmm_{t-1} + \delta_{hhmm} RUCC_{t-1} + u_t \,, \tag{3}$$

where *hhmm* refers to a time of the day in hours and minutes and *hhmm–i* indicates the time *i* minutes prior to *hhmm*. In the case of TOPIX returns, *hhmm* takes the values from 0901 and 1100 for the morning session and from 1231 to 1500 for the afternoon session (from 1301 to 1500 before April 26, 1991 due to a longer lunch break). Therefore, (1000–3) refers to 09:57. However, (0901–1) and (0901–2) indicate 15:00 and 14:59 of the previous day respectively. Likewise, (1231–1) denotes 11:00. The subscript *t* denotes a date during our sample. The second term on the right-hand side of equation (3), $RJ(hhmm-i)_t$, captures serial correlation that lasts a few minutes. Due to the five-minute periodicity discussed in Section I.A. above, the lag order is set at five for this term. The third term $RJhhmm_{t-1}$, is inserted to account for daily periodicity. $RUCC_{t-1}$ is the explanatory variable that is the focus of this exercise and is a daily close-to-close S&P500 return observed just prior to the opening of daily trades in Tokyo. δ_{hhmm} captures the effect of the previous day's close-to-close return in New York on each one-minute return in Tokyo.

Since the Tokyo Stock Exchange is open for four and a half hours each day, there are 270 one-minute returns every day, and we ran 270 regressions for each return and obtained as many coefficient estimates for δ_{hhmm}. The sample period is from January 5, 1988 to November 27, 2003, and the number of observations is 2,374 for returns from 12:31 to 13:00 and 3,001 to 3,034 for others.[12]

Estimation results of equation (3) at 9:01, 12:31, and 14:00 are presented in Table VI. The

[12] The slight difference in the number of observations is due to: 1. a few missing values, 2. a peculiar convention in the TSE whereby only morning sessions are held on the last and first day of the year, 3. during the earlier part of the sample period (before February 1989), two or three Saturdays per month

result for 14:00 (*RJ1400*) is given as a typical example of all other regressions. Figure 6 plots 270 regression estimates of δ_{hhmm} together with their 95% confidence bands. It shows that δ_{0901} is about 0.18 and that the coefficients decline rapidly. Most of the coefficients after 09:06 are trifling in magnitude and are not significantly different from zero. In other words, the Tokyo Stock Exchange reacts to the previous day's movements in New York within the first six minutes after opening. This reaction speed is much faster than that indicated by the correlation coefficients of Figure 4 which exhibit positive correlation with $RUCC_{t-1}$ up to around 09:21. These correlation coefficients only capture the pairwise relation between each one-minute return and $RUCC_{t-1}$, hence they do not account for the lagged effects of immediate past returns. However, the regression equation takes serial correlation into account by adding lagged one-minute returns (the second term on the right-hand side of equation (3)). In fact, these lagged series are significantly positive in most regression equations. Consequently, we have negative evidence on the random walk hypothesis, which requires absence of serial correlation.[13] Presence of serial correlation is also confirmed by autocorrelation coefficients which are significant up to forty minutes.

=================

Figure 6 is about here

=================

================

Table VI is about here

---

were open for trading, but were only for the morning session.

[13] Serial correlation may not contradict the random walk hypothesis when minute-by-minute data is used, since absence of trading, which is likely at such a high frequency, leads to stale prices and therefore serial correlation.

================

Another interesting finding from the regressions is that, while returns in the past few minutes usually have a positive effect on the subsequent returns (see right columns of Table VI), the last return of the day (*RJ1500*) has a significantly *negative* effect on *RJ0901* (see left columns of Table VI). Its coefficient is –0.20 with a *t*-statistic of 6.53. We noted above that there is a tendency for the TOPIX to rise toward the closing of the day (Figure 1), but this is reversed when the market opens the following day.

Another remarkable fact shown in the middle columns of Table VI is that the coefficient for $RUCC_{t-1}$ is significantly negative in a regression for *RJ1231*, which means that the opening price of the afternoon session reverses the reaction at the opening of the morning session. Furthermore, just as *RJ0901* reacts negatively to the previous day's closing ($RJ1500_{-1}$), *RJ1231* reacts negatively to the closing of the morning session (*RJ1100*). The coefficient on *RJ1100* in a regression for *RJ1231* is –0.207 with a *t*-statistic of 6.61.

The left-hand-side variable lagged one day is significant in the regression for *RJ0901* and *RJ1231*, which points to the necessity of including this term. Just one example of all other mundane results is given by the regression for *RJ1400*, in which $RUCC_{t-1}$ is not significant. Three out of five lagged one-minute returns are significant, but the independent variable lagged one day is not.

3.3 Regression analysis: effect of Tokyo on New York

Next, we examine the effects of the Tokyo stock market on New York. We regress each of $RUhhmm_t$ (one-minute returns of S&P500 at each minute of the day t) on a constant, lagged one-minute returns of the preceding three minutes, the return at the same time the day before, and a daily close-to-close return observed in Tokyo prior to the opening of the NYSE:

$$RUhhmm_t = \alpha_{hhmm} + \sum_{i=1}^{3} \beta_{hhmm}^{i} RU(hhmm-i)_t + \gamma_{hhmm} RUhhmm_{t-1} + \delta_{hhmm} RJCC_t + u_t \, , \tag{4}$$

where $RJCC_t$ is the daily close-to-close return of the TOPIX observed eight and a half hours before the opening of the New York stock market. As in equation (3), we include lagged one-minute returns (the second term on the right-hand side of (4)), but the lag order is three, which seems to be enough to capture the very short-run serial correlation in *RUhhmm*.

Estimation results at 09:31 and 15:00 are presented in left and middle columns of Table VII. When the NYSE opens in the morning, $RJCC_{t-1}$ has a significantly positive and the lagged dependent variable ($RU0931_{t-1}$) a significantly negative effect on *RU0931*. But the previous day's final one-minute return at the closing has no effect.

The result for *RU1500* is displayed as a typical example of all other regressions, where $RJCC_{t-1}$ has no effect. Of the three lagged one-minute returns, only that of one minute previously is significant. The dependent variable lagged one day is not significant either.

The estimated coefficients on δ_{hhmm} are presented in Figure 7. Comparing Figure 7 with Figure 6, we initially notice that the first several coefficients in Figure 7 are significant but that they are much smaller in magnitude than those in Figure 6. Thus, the effect of the Tokyo stock market on the New York market is far weaker than the reverse effect. There are possibly two reasons for the small effect of Tokyo on New York. First, the U.S. economy is apparently more important to the Japanese economy than the other way round. In fact, the dominant effect of the U.S. stock prices on other countries' stock prices is well documented in many studies (e.g., Eun and Shim (1989)). Second, although New York is the nearest predecessor to Tokyo, closing right before Tokyo opens, the NYSE opens eight and a half hours after the TSE closes. In the meantime Frankfurt and London start their daily trading before New York. Tsutsui and Hirayama (2004a) analyze these four countries using daily closing prices and report a finding that the market which closes immediately before one market has the largest effect. In light of this finding, it would be natural to have a small effect of Tokyo on New York due to the intervening effects of Frankfurt and London.

=================
Figure 7 is about here
=================

To account for these effects, we include the daily close-to-close return in FAZ Index of Frankfurt Stock Exchange ($RGCC_t$) in the regression equation:

$$\begin{aligned} RUhhmm_t = \alpha_{hhmm} + \sum_{i=1}^{3} \beta_{hhmm}^{i} RU(hhmm-i)_t \\ + \gamma_{hhmm} RUhhmm_{t-1} + \delta_{hhmm} RJCC_t + \varepsilon_{hhmm} RGCC_t + u_t , \end{aligned} \tag{5}$$

where ε_{hhmm} captures the effect of Frankfurt on New York. The effect of London's daily closing cannot be incorporated, because London's closing time is later than the opening of the NYSE (see Figure 2). London closes its daily trading at 16:30 GMT, which is 11:30 EST in New York.

Namely, when New York opens at 09:30 local time, London's closing value is not yet known. Thus, we had to drop London's daily close-to-close return variable.[14] The Frankfurt Stock Exchange, on the other hand, is open for trading between 10:30 and 13:30 local time. This closing time is two hours before opening of New York (Figure 2). Frankfurt's daily close-to-close return is known to New York, the effect of which is captured by ε_{hhmm} in equation (5) above.

We ran a regression for this equation and the estimated ε_{0931} is about 0.042[15] (see the right columns of Table VII) which is greater than $\delta_{0931} = 0.028$ in equation (4) (see the left columns of Table VII). However, it is only one-quarter of the effect of New York on Tokyo (see the left columns of Table VI and $0.178 \div 4 \approx 0.045$). The result seems to vindicate our two conjectures above offered as an explanation for the small effect of Tokyo on New York. Though this smallness is partly caused by the intervening market in Frankfurt, Frankfurt's effect on New York is also very small compared with the effect of New York on Tokyo, which implies a dominant influence of New York on other markets.

================
Table VII is about here
================

We report, in passing, the estimated δ_{0931} in equation (5). It is now 0.015, which is roughly half that in equation (4). δ_{0932} is also significantly positive, but not after the first two

[14] If we had intra-day data of London, we could compute a return up to the time of New York's opening to capture the effect of London on New York. Unfortunately we could obtain only daily closing prices for London and Frankfurt, which compelled us to disregard this effect of London.
[15] This coefficient does not change much even if $RJCC_t$ is excluded from equation (5).

minutes. This reduction implies that about half of Tokyo's effect on New York as measured by equation (4) is absorbed by Frankfurt.

Next, in Figure 7, coefficients up to *RU0944* tend to be significant, which means it takes the NYSE about fourteen minutes to absorb new information from Tokyo. Closer inspection reveals that eight out of fourteen coefficients on $RJCC_t$ are statistically significant. The first two coefficients at 09:31 and 09:32 are significant at a 5% significance level, but subsequently they are significant in regressions for *RU0934*, *RU0938*, *RU0939*, *RU0940*, *RU0943*, and *RU0944*. When we examine the effect of Frankfurt on New York in equation (5), it is significant for most of the first fifteen minutes after 09:31.[16] Since the reaction time is six minutes in Tokyo, the reaction time of New York is longer than that of Tokyo.

In view of the fact on the serial correlation shown below, the above results should not be interpreted that TSE is generally more efficient than NYSE. It may be explained by the fact that the opening price of the Tokyo Stock Exchange is formed by a batch process (*itayose*, see Footnote 7), in which trading orders are accepted during sixty minutes prior to the market opening at 09:00. However, in the New York Stock Exchange, the usual continuous trading process determines the opening price. We infer, then, that the stale-price problem is more serious in New York.

A careful perusal of the regression results reveals some interesting contrasts between the two markets. First, in New York, the effects of the three lagged one-minute returns are significant during the first ten minutes after opening, but for the rest of the day, only the immediately preceding one-minute return is significant. However, in Tokyo, many, if not all, of the five lagged returns are always significant throughout the day. In other words, serial correlation in one-minute returns is more apparent in Japan than in New York (compare right columns of Table VI and middle columns of Table VII). This is also supported by evidence from autocorrelation coefficients. They indicate correlations are significant for up to forty minutes in Tokyo but only up to ten minutes in New York (results are not shown). The results may support the view that NYSE is more informationally efficient than TSE (see Footnote13).

Another difference is that, in New York, the previous day's closing price does not affect the opening price, but it does so in a significantly negative way in Tokyo (compare left columns of Tables VI and VII). These differences must be explained by different market microstructure, which is left as a question for future investigation.

3.4 What returns do the markets react to?

In the previous section, we assume that the markets react to daily close-to-close returns. Since the media, such as TV and newspapers, regularly announce this return, this assumption is reasonable. In this subsection, we will investigate whether the markets react to the information from more specific periods than the close-to-close return.

The close-to-close return of the TOPIX (*RJCC*) can be divided into a close-to-open

---

[16] This result is basically unaltered even if $RJCC_t$ is dropped from equation (5).

return (*RJ0901*; nontrading-hours return) and an open-to-close return (*RJOC*; trading-hours return). *RJOC* can further be divided into a morning return (*RJMN*; 9:01 to 12:31) and an afternoon return (*RJAN*; 12:31 to 15:00).

Likewise, the close-to-close return of S&P500, *RUCC*, is divided into a close-to-open return, *RUCO*, an open-to-close return, *RUOC*, a morning return, *RUMN*, and an afternoon return, *RUAN*, where morning means 9:31 to 13:00 and afternoon is 13:01 to 16:00.[17]

Let us first look at correlations between these returns, which are shown in Table VIII. While *RUOC* highly correlates with *RUCC* (coefficient is 0.995), the correlation coefficient between *RUCO* and *RUCC* is only 0.28. Actually, *RUOC* is almost identical to *RUCC*, which can also be ascertained by their means and standard deviations in Table V. This fact leads us to expect that the Tokyo market reacts to *RUOC* just the same way as to *RUCC* in equation (3). Indeed, replacing *RUCC* with *RUOC* in regression equation (3) yields nearly the same results. The same applies to *RJOC* and *RJCC* in equation (4).

================
Table VIII is about here
================

In order to find out which return the markets react to, we compare the explanatory power of the returns in equation (3) or in equation (4). For the ease of exposition, let us refer to equation (3) as Model A and the equation in which *RUCC* is replaced with some other return as Model B. Construction of these models requires a non-nested test, because neither is a subset of

[17] *RUCO* is the close-to-open overnight return, which is slightly different from *RU0931* that is defined

the other model. In this paper we apply Deaton's *F* test (Deaton, 1982).[18] In this test, we compare Model A and B, and focus on the variables that are not included in the other model. In the test of Model A (equation 3) vs. Model B (*RUxx* replaces *RUCC* in equation 3), equation (3) is run first; then we add the alternative return variable and test the explanatory power of this variable by a standard *F* test (equivalent to a *t* test, since there is only one additional variable). If the additional variable is statistically significant, Model B is selected over Model A. In the test of Model B vs. Model A, Model B is run first; then we add *RUCC* and test the explanatory power of *RUCC*. If *RUCC* is significant, Model A is selected over Model B. Naturally, a pair of these tests may not produce an unequivocal result.

P-values of the test for the first seven minutes of TOPIX returns are presented in Table IX, since the first six minutes are the time the Tokyo market significantly reacts to New York. In the left columns, we compare additional explanatory power of *RUOC* and *RUCC*. When *RUOC* is added to equation (3) (Model A), *RUOC* is significant at a 10% level for three cases out of seven (see the second column).[19] The third column shows the results when *RUCC* is added to Model B. Three cases out of seven cases are significant, implying *RUOC* and *RUCC* have almost the same explanatory power. The result is reasonable because *RUOC* and *RUCC* are almost identical series.

---

as the return between 16:00 in the previous day and 09:31. See Note 10.

[18] The *J* test (Davidson and MacKinnon, 1981) and the double log likelihood ratio test are alternative tests of non-nested models.

[19] We also provide the number of significant cases at a 5% level in the Table, which leads to the same conclusions.

================
Table IX is about here
================

Comparing *RUCO* and *RUCC*, while *RUCC* is significant in six cases, *RUCO* is significant only in three cases. This implies that the close-to-close return is more important and is the one focused on by Japanese investors. Similar results are obtained for the morning return (*RUMN*) and the afternoon return (*RUAN*). In summary, Table IX suggests that the Tokyo market watches the close-to-close return more than other returns, probably because this is what the media usually reports. *RUOC* has strong explanatory power simply because it is almost identical to *RUCC*.

The same procedure is applied to equation (4) to compare the explanatory power of *RJCC* with other returns such as *RJOC* and the results for the first fifteen minutes are shown in Table X. In the first pair, *RJOC* is significant in six cases at a 10% level, just as *RJCC* is. *RJ0901* is significant in six cases, *RJCC* in fourteen cases. *RJMN* and *RJAN* are significant only in one and two cases, while *RJCC* is significant in eight cases. These results suggest the same conclusion as the Tokyo market: the close-to-close return of TOPIX is what the U.S. investors focus on.

================
Table X is about here
================

4. Changes in the linkage over sub-periods

In order to examine whether the response pattern has changed during our sample period, we divide the whole sample into three subperiods and conduct the same analysis of the previous section. Figure 8 shows the daily closing prices of S&P500 and TOPIX. It seems reasonable to divide the whole period into the following three subperiods:

Period I: January 5, 1988 to December 31, 1989 when stock prices exhibited an upward trend in both the U.S. and Japan.

Period II: January 4, 1990 to October 15, 1998, when stock prices in the U.S. exhibited an upward trend, while those in Japan fell significantly at first and were stagnant thereafter.

Period III: October 16, 1998 to November 27, 2003, when stock prices in both countries moved in a similar fashion, exhibiting an inverted U-shaped pattern.

=================

Figure 8 is about here

=================

We regress equation (3) by OLS and the sum of coefficients on $RUCC_{t-1}$ in regressions for *RJhhmm* cumulated over each one-minute interval is depicted in Figure 9 for the Tokyo stock market. Thus, the graph shows cumulative effects of the S&P500 on the TOPIX during the course of a day's trading. Individual coefficients are statistically significant only at the beginning of the day. Others are seldom significant, thus rendering the cumulative sums statistically not very meaningful. However, even though they are not different from zero statistically, whenever they tend to be positive over successive minutes the cumulative sum tends to rise, which does imply that the effect from the other market is cumulatively positive.

Thus, aside from strict statistical significance, we can infer a general direction of the other market's influence during the day from this graph. Figure 9, which plots these cumulative sums for three subperiods, reveals the following:

1) The efficiency in terms of length of reaction time has increased over the sixteen-year period. In Period I, positive responses continue until around 09:30 and thereafter negative responses follow during the morning session. In Period II, positive responses dissipate by around 09:15 and the decline afterwards is much smaller. Period III exhibits a rapid increase after the opening and the peak is observed at 09:06, indicating a rise in efficiency in absorbing effects from New York.

2) The magnitude of the cumulative reaction has become greater, from around 0.1 for Period I to 0.3 for Period III. Two reasons can be offered. One is that the increase reflects intensified economic integration between the U.S. and Japan. The other is that the relative size of the Tokyo stock market to the New York stock market, as measured by annual turnover, has declined over the period. Figure 10 plots the annual turnover in New York and Tokyo Stock Exchanges. Tokyo's turnover exceeded that of New York in 1988 and 1989. However, the Japanese stock prices have declined and stagnated since then, whereas the New York market has seen a spectacular rise in the 1990s. Thus, the U.S. turnover has grown tremendously, dwarfing that of Tokyo.

3) A *negative* response at the opening of the afternoon session is visible in all three

subperiods. In Period I when the afternoon session started at 13:00 this negative response is observed at 13:01.

=================
Figures 9 and 10 are about here
=================

Cumulative sums of coefficients on *RJCC* in regression equation (4) for the New York stock market are displayed in Figure 11. Efficiency seems to have improved from Period I to Period II. Specifically, positive responses, small in magnitude, continue for about two hours after the opening in Period I, but in Periods II and III initial positive responses abate in about fifteen minutes after opening. The overall magnitude of cumulative responses is much higher in Period III than in Period I or II. However, it is much smaller than that of Tokyo. This is probably due to the relative importance of the economy.

=================
Figure 11 is about here
=================

5. Is there asymmetry in the reaction as the other market rises or falls?

In order to see if there is asymmetry in responses to the other market's rise or fall, we regress Japanese returns on positive $RUCC_{t-1}$ and on negative $RUCC_{t-1}$ separately. Although the regression equation is equation (3), we divide the observations into one group where $RUCC_{t-1}$ is positive and another where $RUCC_{t-1}$ is negative. Thus, we ran two sets of regressions. The resultant estimates are displayed in Figure 12, in which cumulative sums of coefficients are shown. The cumulative responses to the positive and negative $RUCC_{t-1}$ are remarkably similar.

=================
Figure 12 is about here
=================

Likewise, estimating equation (4) with positive and negative $RJCC_t$ separately, we compute the cumulative sums of coefficients for the New York stock market reacting to positive and negative $RJCC_t$ values which are depicted in Figure 13. Unlike Tokyo, New York exhibits clear asymmetry in reaction. Bad news from Japan has a considerably stronger effect on New York than good news. The magnitude of the response in New York to a fall in Tokyo is roughly double that of a rise. The response pattern is also different: when Tokyo has advanced, responses in New York are spread over a longer period, about one and a half hours, but when Tokyo has fallen, positive responses swiftly reach a peak within about fourteen minutes. This asymmetry in reaction to a rise or fall in Tokyo is in contrast to the finding of Tokyo's symmetric responses to New York.[20]

=================
Figure 13 is about here
=================

This asymmetry in New York might be strongly influenced by the rapid declines in the TOPIX during the period from January 1990 to July 1992 (see Figure 8). To check on this possibility, we divided the sample into three subperiods as above and ran the same regressions.

---

[20] Analyzing the daily stock price index data from 1975 to 1995 for the U.S., the U.K., Germany, and Japan, Hirayama and Tsutsui (1998b) found that negative large changes have a clearer effect than positive ones.

We again obtained asymmetric responses in New York to a rise or fall in Japan in all three subperiods, indicating asymmetry throughout the sixteen-year period. Why investors in New York are more sensitive about the fall in Tokyo is another agenda for future research.

6. Conclusions

This paper explores how rapidly the Tokyo and New York stock markets respond to the movements of the stock price index of the other market using high-frequency data over the period from January 5, 1988 to November 27, 2003. Estimating the reactions of one-minute returns of one country to the preceding daily return of the other country, we find that:

1) A positive response of the Tokyo stock market dissipates within six minutes, while that of New York dissipates within fourteen minutes, implying that both markets are fairly efficient. The TSE is more efficient in absorbing the impact at the opening than NYSE, possibly because TSE employs a batch process called *itayose* for forming the opening price.
2) The magnitude of the response is around 0.054 (cumulative sum for the first fourteen minutes) for the New York stock market and 0.22 (cumulative sum for the first six minutes) for Tokyo. Thus, the effect of New York on Tokyo is over four times greater than the reverse effect.
3) The efficiency of the two markets measured by the response time has improved over the

period. The magnitude of the response has grown for the Tokyo stock market over the three periods, while that of the New York stock market has grown between the first and the second period.

4) The response of the Tokyo stock market is symmetric in terms of a fall or rise in New York, while the response of the New York stock market to a fall in Tokyo is twice as great as that to a rise.

5) The opening price of the afternoon session of the Tokyo stock market negatively responds to the previous movement in New York.

Determining the causes of interesting findings 4) and 5) remains an agenda for future research. We suggested, however, that 5) is the result of giving a second thought over lunch to the excessive response at the opening of the day.

The reaction time is on the average six minutes for Japan and fourteen minutes for the U.S. This is consistent with the findings on stock price reactions to earnings and dividend announcements (Patell and Wolfson (1984)), but it is far slower than adjustments in foreign exchange markets which typically adjust to news announcements within one minute (Ederington and Lee (1995)). The difference may be explained by the different nature of the two markets. There are vastly more participants, both individuals and institutional investors, in a stock market than in a foreign exchange market. The stock market is also a place of the 'beauty contest' as Keynes once likened it, where investors carefully observe others before deciding on their strategy. Market participants in foreign exchange are primarily professional dealers and institutional investors who have access to electronic news releases, etc., and are, thus, able to execute transactions extremely rapidly.

The different response time at the market opening can be partly explained by the *itayose* process of matching buy and sell orders in the TSE. The market microstructure must play a role in determining the response time, which is an agenda for the future. Different behavioral patterns may also be a part of the picture, but we await research in behavioral finance comparing the two markets' participants. [21]

[21] According to a questionnaire survey of stock investors in both Japan and the U.S. reported in Shiller *et al*. (1996), wishful thinking distinctly characterizes Japanese investors.

References

Almeida, A., C. A. E. Goodhart, and R. Payne, 1998, The Effects of Macroeconomic News on High Frequency Exchange Rate Behavior, *Journal of Financial and Quantitative Analysis* 33 (3), 383–408.

Amihud, Y. and H. Mendelson, 1991, Volatility, efficiency, and trading: evidence from the Japanese stock market, *Journal of Financ*e 66 (5), 1765–1789.

Andersen, T. G., T. Bollerslev, and J. Cai, 2000, Intraday and interday volatility in the Japanese Stock Market, *Journal of International Financial Markets, Institutions and Money* 10, 107–130.

Becker, K. G., J. E. Finnerty, and A. L. Tucker, 1992, The Intraday interdependence structure between U.S. and Japanese equity markets, *Journal of Financial Research* 15 (1), 27–37.

Blackman, S.C., K. Holden, and W. A. Thomas, 1994, Long-term relationships between international share prices, *Applied Financial Economics* 4, 297–304.

Chan, K. C., B. E. Gup, and M. S. Pan, 1992, An empirical analysis of stock prices in major Asian markets and the United States, *The Financial Review* 27 (2), 289–307.

Choudhry, T., 1994, Stochastic trends and stock prices: an international inquiry, *Applied Financial Economics* 4 (6), 383–390.

Choudhry, T., 1997, Stochastic trends in stock prices: evidence from Latin American markets, *Journal of Macroeconomics* 19 (2), 285–304.

Chung, P. J. and D. J, Liu, 1994, Common stochastic trends in Pacific Rim stock markets, *The Quarterly Review of Economics and Finance* 34 (3), 241–259.

Corhay, A., A. Tourani Rad, and J.-P. Urbain, 1993, Common stochastic trends in European stock markets, *Economics Letters* 42, 385–390.

Dacorogna, M. M., R. Gençay, U. A. Müller, R. B. Olsen, and O. V. Pictet, 2001, An introduction to high-frequency finance (San Diego and London: Academic Press).

Davidson, R. and J. G. MacKinnon, 1981, Several tests for model specification in the presence of alternative hypotheses, *Econometrica* 49, 781–793.

Deaton, A. S., 1982, Model selection procedures, or does the consumption function exist? in G. C. Chow and P. Corsi eds.: Evaluating the reliability of macro-economic models (Wiley, London) Chap. 5.

Ederington, L. H. and J. H. Lee, 1995, The short-run dynamics of the price adjustment to new information, *Journal of Financial and Quantitative Analysis* 30 (1), 117–134.

Eun, C. S. and S. Shim, 1989, International transmission of stock market movements, *Journal of Financial and Quantitative Analysis* 24 (2), 241–256.

Goodhart, C. A. E. and M. O'Hara, 1997, High frequency data in financial markets: issues and applications, *Journal of Empirical Finance* 4 (2–3), 73–114.

Hirayama, K. and Y. Tsutsui, 1998a, Intensifying international linkage of stock prices: cointegration and VEC analysis, *Osaka Economic Papers* 48 (1), 1–17.

Hirayama, K. and Y. Tsutsui, 1998b, Threshold effect in international linkage of stock prices, *Japan and the World Economy* 10 (4), 441–453.

Jain, P. G., 1988, Response of hourly stock prices and trading volume to economic news, *Journal of Business* 61, 219–231.

Jeon, B. N. and T. C. Chiang, 1991, A system of stock prices in world stock exchanges: common stochastic trends for 1975–1990? *Journal of Economics and Business* 43 (4), 329–338.

Jeon, B. N. and G. B. von Furstenberg, 1990, Growing international co-movement in stock price indexes, *Quarterly Review of Economics and Business* 30 (3), 15–30.

Kasa, K., 1992, Common stochastic trends in international stock markets, *Journal of Monetary Economics* 29, 95–124.

Mathur, I. and V. Subrahmanyam, 1990, Interdependence among the Nordic and U.S. stock markets, *Scandinavian Journal of Economics* 92 (4), 587–597.

Patell, J. and M. Wolfson, 1984, The intraday speed of adjustment of stock prices to earnings and dividend announcements, *Journal of Financial Economics* 13, 223–252.

Shiller, R. J., F. Kon-Ya, and Y. Tsutsui, 1996, Why did the Nikkei crash? Expanding the scope of expectation data collection, *Review of Economics and Statistics* 78 (1), 156–164.

Tsutsui, Y., 2002, The interdependence and its cause of the Japanese and U.S. stock prices: an event study. *Asian Economic Journal* 16 (2), 97–109.

Tsutsui, Y., 2003, Stock prices in Japan rise at night, *Japan and the World Economy* 15 (4), 391–406.

Tsutsui, Y. and K. Hirayama, 2004a, Appropriate lag specification for daily responses of international stock markets, Forthcoming in *Applied Financial Economics*.

Tsutsui, Y. and K. Hirayama, 2004b, Are the international portfolio adjustments a cause of the comovements of stock prices? *Pacific Basin Finance Journal* 12, 463–478.

Tsutsui, Y. and K. Hirayama, 2004c, Estimation of the Common and Country-Specific Shock to Stock Prices, forthcoming in *Journal of the Japanese and International Economies.*

Table I. Summary Statistics of Selected TOPIX Returns

	Mean	Max.	Min.	S.D.	LB Q(5)	N. Obs.
RJCC	–0.005414	9.544252	–7.099952	1.241356	0.000000	3946
RJOC	–0.028921	9.535624	–7.077842	1.120321	0.000000	3946
RJMN	–0.061056	4.928397	–7.383014	0.848256	0.000000	3878
RJAN	0.027906	4.986915	–4.181279	0.651292	0.000000	3882
RJ0901	0.022538	1.290985	–1.384551	0.300236	0.000000	3946
RJ0902	0.009977	0.531608	–0.467999	0.122559	0.000444	3946
RJ0903	0.002953	0.313808	–0.370573	0.066933	0.133961	3946
RJ0904	0.002050	0.335886	–0.307720	0.053931	0.281170	3946
RJ0905	–0.000182	0.304305	–0.259738	0.049527	0.015431	3946
RJ0906	0.005068	0.874180	–0.837865	0.129583	0.000406	3946
RJ0907	–0.000177	0.372772	–0.415340	0.054780	0.020173	3946
RJ0908	–0.000180	0.293806	–0.294364	0.048681	0.194841	3946
RJ0909	–0.002076	0.287059	–0.336252	0.046205	0.040236	3946
RJ0910	–0.001682	0.257447	–0.231399	0.042652	0.040273	3946
RJ0911	–0.000919	0.628561	–0.678866	0.070972	0.000000	3946
RJ0912	–0.001643	0.338236	–0.303619	0.043420	0.148306	3946
RJ0913	–0.002397	0.225850	–0.258847	0.041816	0.389702	3946
RJ0914	–0.001593	0.265057	–0.300950	0.041100	0.538632	3946
RJ0915	–0.000664	0.331735	–0.263754	0.040282	0.188328	3946
RJ1231	–0.020839	0.495607	–0.512869	0.110544	0.000000	3080
RJ1232	–0.006396	0.374045	–0.272433	0.053161	0.000522	3080
RJ1233	–0.004164	0.233465	–0.237738	0.036479	0.191377	3080
RJ1456	0.002471	0.336507	–0.223676	0.042856	0.810936	3891
RJ1457	0.002008	0.295976	–0.361518	0.044994	0.757910	3891
RJ1458	0.006019	0.310071	–0.434954	0.050495	0.505516	3891
RJ1459	0.007532	0.429410	–0.331767	0.053642	0.147413	3891
RJ1500	0.031975	0.881639	–0.613469	0.142120	0.000000	3891

Notes: Variables are TOPIX returns (in percent). *RJOC* is daily open-to-close return, *RJMN* morning return from 09:01 to 12:31 (opening of the afternoon session), *RJAN* afternoon return from 12:31 to 15:00. *RJhhmm* where *hhmm* is 0902, …, 1500 is a one-minute return except *RJ0901* which is daily close-to-open (overnight) return and *RJ1231* which is a 61-min. return over the lunch break. S.D. is the standard deviation. LB Q(5) is the Ljung–Box Q statistic which tests the null hypothesis that every autocorrelation coefficient up to the fifth order is zero. *p*-values are shown in this column. The sample period is from January 5, 1988 to November 27, 2003. See Footnote 12 for the reasons for different numbers of observations.

Table II. Correlation Coefficients between TOPIX 8-Min. Return at Closing

and Selected TOPIX Returns

	RJ08M1500	*RJ0901*	*RJ14M0915*	*RJ0901*$_{+1}$	*RJ14M0915*$_{+1}$
RJ08M1500	1.0000				
RJ0901	0.0104	1.0000			
RJ14M0915	0.0267	0.5741	1.0000		
RJ0901$_{+1}$	–0.0306	0.0806	0.0428	1.0000	
RJ14M0915$_{+1}$	–0.0115	0.0214	0.0348	0.5740	1.0000

Notes: *RJ08M1500* is the last 8-min. return to closing at 15:00, *RJ0901* the close-to-open overnight return, *RJ14M0915* a 14-min. return to 09:15, and *RJCC* the daily close-to-close return. The subscript, $_{+1}$, denotes a one-day lead (the next day).

Table III. Correlation Coefficients between Selected TOPIX Returns

	RJ0901	*RJ45M1000*	*RJ1231*
RJ0901	1.0000		
RJ45M1000	–0.0288	1.0000	
RJ1231	–0.0348	0.0554	1.0000

Notes: *RJ0901* is the overnight return from the previous day's close to the opening, *RJ45M1000* is the 45-min. return from 09:15 to 10:00, and *RJ1231* is the one-and-a-half hour return during the lunch break. The sample period is from April 30, 1991 to November 27, 2003.

Table IV. OLS Regressions to Explain *RJ1231*

	Eq. (i)		Eq. (ii)		Eq. (iii)	
Variable	Coeff.	*p*-val.	Coeff.	*p*-val.	Coeff.	*p*-val.
Constant	–0.018	0.000	–0.020	0.000	–0.017	0.000
RJ0901	–0.013	0.062	–0.011	0.065	–0.011	0.109
RJ45M1000			0.016	0.003	0.019	0.004
RJ1100	–0.205	0.000			–0.208	0.000
RJ1059	0.103	0.102			0.096	0.124
RJ1058	0.066	0.321			0.064	0.335
RJ1057	–0.011	0.874			–0.012	0.862
RJ1056	0.101	0.122			0.099	0.129
$RJ1231_{-1}$	0.082	0.000			0.083	0.000
$\bar{R}^2$	0.023		0.004		0.026	
p-value of *F* test	0.000		0.002		0.000	
Num. of Obs.	2371		3077		2371	

Notes: The dependent variable is *RJ1231*, over-lunch return from 11:00 to 12:31. *RJ0901* is the overnight return from the previous day's close to the opening price at 09:01. *RJ45M1000* is the 45-min. return from 09:15 to 10:00. *RJhhmm*, where *hhmm* is 1056, …,1100, is the one-minute return up to *hhmm*. The subscript, $_{-1}$, denotes a one-day lag. The sample period is from April 30, 1991 to November 27, 2003. The sample size is reduced in equations (i) and (iii) relative to equation (ii) due to the lagged dependent variable on the right-hand side.

Table V. Summary Statistics of Selected S&P500 Returns

	Mean	Max.	Min.	S.D.	LB Q(5)	N. Obs.
RUCC	0.041675	5.451431	–6.865681	1.042395	0.019949	4014
RUOC	0.036210	6.205689	–6.865681	1.017440	0.013549	4014
RUMN	–0.003487	4.023462	–4.341921	0.758387	0.000017	4014
RUAN	0.039431	5.018159	–5.240286	0.637614	0.000000	4014
RU0931	0.008265	1.401524	–1.649356	0.187130	0.000000	4014
RU0932	0.001432	0.886300	–0.591704	0.079346	0.000035	4014
RU0933	0.003773	0.677632	–0.487086	0.071638	0.000000	4014
RU0934	0.002902	0.602593	–1.214823	0.070406	0.000022	4014
RU0935	0.001415	0.434428	–0.502196	0.061016	0.477687	4014
RU0936	0.001634	0.566342	–0.269207	0.056813	0.008024	4014
RU0937	0.001818	0.371824	–0.587030	0.053691	0.010459	4014
RU0938	0.000900	0.367519	–0.950650	0.054016	0.035783	4014
RU0939	0.000352	0.369199	–0.588413	0.050169	0.088257	4014
RU0940	–0.000672	0.975905	–1.347478	0.056239	0.012359	4014
RU0941	0.000453	1.419375	–0.320305	0.048864	0.228742	4014
RU0942	–0.000378	0.273372	–0.920964	0.048071	0.118098	4014
RU0943	–0.000724	0.333264	–0.375926	0.043056	0.014997	4014
RU0944	–0.000625	0.845680	–0.402200	0.044064	0.189095	4014
RU0945	–0.001040	0.622440	–0.374209	0.042680	0.144755	4014
RU0946	–0.000456	1.035158	–0.320899	0.042752	0.075252	4014
RU0947	–0.000024	0.295632	–0.401757	0.042440	0.274315	4014
RU0948	–0.000946	0.498991	–0.415385	0.042172	0.013457	4014
RU0949	–0.000868	0.312094	–0.381088	0.041142	0.782206	4014
RU0950	–0.001124	0.318218	–0.412264	0.041282	0.006747	4014
RU1556	0.000446	0.225533	–0.161202	0.026527	0.515950	4014
RU1557	0.000957	0.223683	–0.170993	0.026275	0.482934	4014
RU1558	0.001198	0.132838	–0.212960	0.025592	0.061886	4014
RU1559	0.002425	0.224797	–0.189719	0.026541	0.180678	4014
RU1600	0.001906	0.189216	–0.231702	0.026650	0.115109	4014

Notes: Variables are several S&P500 returns. *RUCC* is daily close-to-close return, *RUOC* daily open-to-close return, *RUMN* morning return from 09:31 to 13:00, and *RUAN* afternoon return from 13:01 to 16:00. *RUhhmm* where *hhmm* is 0932, …, 1600 is a one-minute return except *RU0931* which is close-to-open (overnight) return. S.D. is the standard deviation. LB Q(5) is the Ljung-Box Q statistic which tests the null hypothesis that every autocorrelation coefficient up to the fifth order is zero. *p*-values are shown in this column. The sample period is from January 5, 1988 to November 27, 2003.

Table VI. Selected Estimation Results of Eq. (3)

RJ0901			*RJ1231*			*RJ1400*		
Variable	Coeff.	*p*-val.	Variable	Coeff.	*p*-val.	Variable	Coeff.	*p*-val.
Constant	0.017	0.000	Constant	–0.017	0.000	Constant	0.000	0.468
$RUCC_{-1}$	0.178	0.000	$RUCC_{-1}$	–0.010	0.000	$RUCC_{-1}$	–0.001	0.200
$RJ1500_{-1}$	–0.202	0.000	*RJ1100*	–0.207	0.000	*RJ1359*	0.098	0.000
$RJ1459_{-1}$	–0.049	0.564	*RJ1059*	0.088	0.156	*RJ1358*	0.054	0.004
$RJ1458_{-1}$	0.039	0.645	*RJ1058*	0.060	0.364	*RJ1357*	0.050	0.006
$RJ1457_{-1}$	–0.012	0.898	*RJ1057*	–0.004	0.951	*RJ1356*	0.020	0.302
$RJ1456_{-1}$	0.145	0.157	*RJ1056*	0.097	0.134	*RJ1355*	0.022	0.237
$RJ0901_{-1}$	0.025	0.085	$RJ1231_{-1}$	0.085	0.000	$RJ1400_{-1}$	–0.004	0.847
$\overline{R}^2$	0.369		$\overline{R}^2$	0.031		$\overline{R}^2$	0.017	
p-val. of *F*	0.000		*p*-val. of *F*	0.000		*p*-val. of *F*	0.000	
Num. Obs.	3034		Num. Obs.	2374		Num. Obs.	3001	

Notes: OLS estimation results of eq. (3) for *RJ0901*, *RJ1231*, and *RJ1400* only are displayed above. The subscript $_{-1}$ indicates a one-day lag. The sample period is from January 5, 1988 to November 27, 2003. '*p*-val.' is the *p*-value of a *t*-statistic on each explanatory variable. '*p*-val. of *F*' is the *p*-value of the *F* test for the entire regression. For different numbers of observations see Footnote 12. The number of observations for *RJ1231* is particularly small because 12:31 was in the middle of a lunch break before April 26, 1991.

Table VII. Selected Estimation Results of Equations (4) and (5)

eq. (4) *RU0931*			eq. (4) *RU1500*			eq. (5) *RU0931*		
Variable	Coeff.	p-val.	Variable	Coeff.	p-val.	Variable	Coeff.	p-val.
Constant	0.010	0.003	Constant	0.001	0.143	Constant	0.010	0.002
RJCC	0.028	0.000	*RJCC*	–0.0002	0.582	*RJCC*	0.015	0.000
						RGCC	0.042	0.000
$RU1600_{-1}$	0.003	0.980	*RU1459*	0.327	0.000	$RU1600_{-1}$	–0.106	0.405
$RU1559_{-1}$	0.125	0.368	*RU1458*	0.002	0.925	$RU1559_{-1}$	0.072	0.593
$RU1558_{-1}$	0.250	0.070	*RU1457*	–0.019	0.309	$RU1558_{-1}$	0.094	0.483
$RU0931_{-1}$	–0.170	0.000	$RU1500_{-1}$	0.014	0.392	$RU0931_{-1}$	–0.192	0.000
$\bar{R}^2$	0.049		$\bar{R}^2$	0.112		$\bar{R}^2$	0.135	
p-val. of F	0.000		p-val. of F	0.000		p-val. of F	0.000	
Num. Obs.	3148		Num. Obs.	3148		Num. Obs.	3085	

Notes: OLS estimation results of eq. (4) for *RU0931*, *RU1500* and of eq. (5) for *RU0931* are displayed above. The subscript , $_{-1}$, indicates a one-day lag. Sample period is from January 5, 1988 to November 27, 2003. '*p*-val.' is the *p*-value of a *t*-statistic on each explanatory variable. '*p*-val. of *F*' is the *p*-value of the *F* test for the entire regression.

Table VIII. Correlation Coefficients between Selected S&P500 and TOPIX Returns

(a) S&P500 Returns

	RUCC	*RUCO*	*RUOC*	*RUMN*	*RUAN*
RUCC	1.0000				
RUCO	0.2805	1.0000			
RUOC	0.9948	0.1813	1.0000		
RUMN	0.7872	0.2399	0.7810	1.0000	
RUAN	0.6512	0.0043	0.6668	0.0554	1.0000

Note: See notes to Table V for definition of the variables.

(b) TOPIX Returns

	RJCC	*RJ0901*	*RJOC*	*RJMN*	*RJAN*
RJCC	1.0000				
RJ0901	0.5027	1.0000			
RJOC	0.9728	0.2889	1.0000		
RJMN	0.8250	0.3584	0.8178	1.0000	
RJAN	0.6023	0.0313	0.6586	0.1056	1.0000

Note: See notes to Table I for definition of the variables. Note that *RJ0901* is the overnight return. *RUCO* is the close-to-open return of S&P500. See Footnote 10 for a minor discrepancy between *RUCO* and *RU0931*

Table IX. Explanatory Power of *RUCC* and Other Returns: Deaton's *F*-tests

	A vs. B *RUOC*	B vs. A *RUCC*	A vs. B *RUCO*	B vs. A *RUCC*	A vs. B *RUMN*	B vs. A *RUCC*	A vs. B *RUAN*	B vs. A *RUCC*
RJ0901	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
RJ0902	0.00000	0.00000	0.00000	0.00000	0.74465	0.00000	0.31186	0.00000
RJ0903	0.34841	0.78735	0.34440	0.00000	0.00453	0.00000	0.00312	0.00763
RJ0904	0.51279	0.82115	0.51505	0.00015	0.81587	0.01247	0.93004	0.00370
RJ0905	0.29450	0.53887	0.30192	0.00048	0.34411	0.00097	0.24866	0.02995
RJ0906	0.00296	0.00018	0.00365	0.00000	0.07003	0.00016	0.01774	0.00000
RJ0907	0.43549	0.38935	0.43960	0.40759	0.24951	0.79681	0.19353	0.16491
10% signif.	3	3	3	6	3	6	3	6
5% signif.	2	3	3	6	2	6	3	6

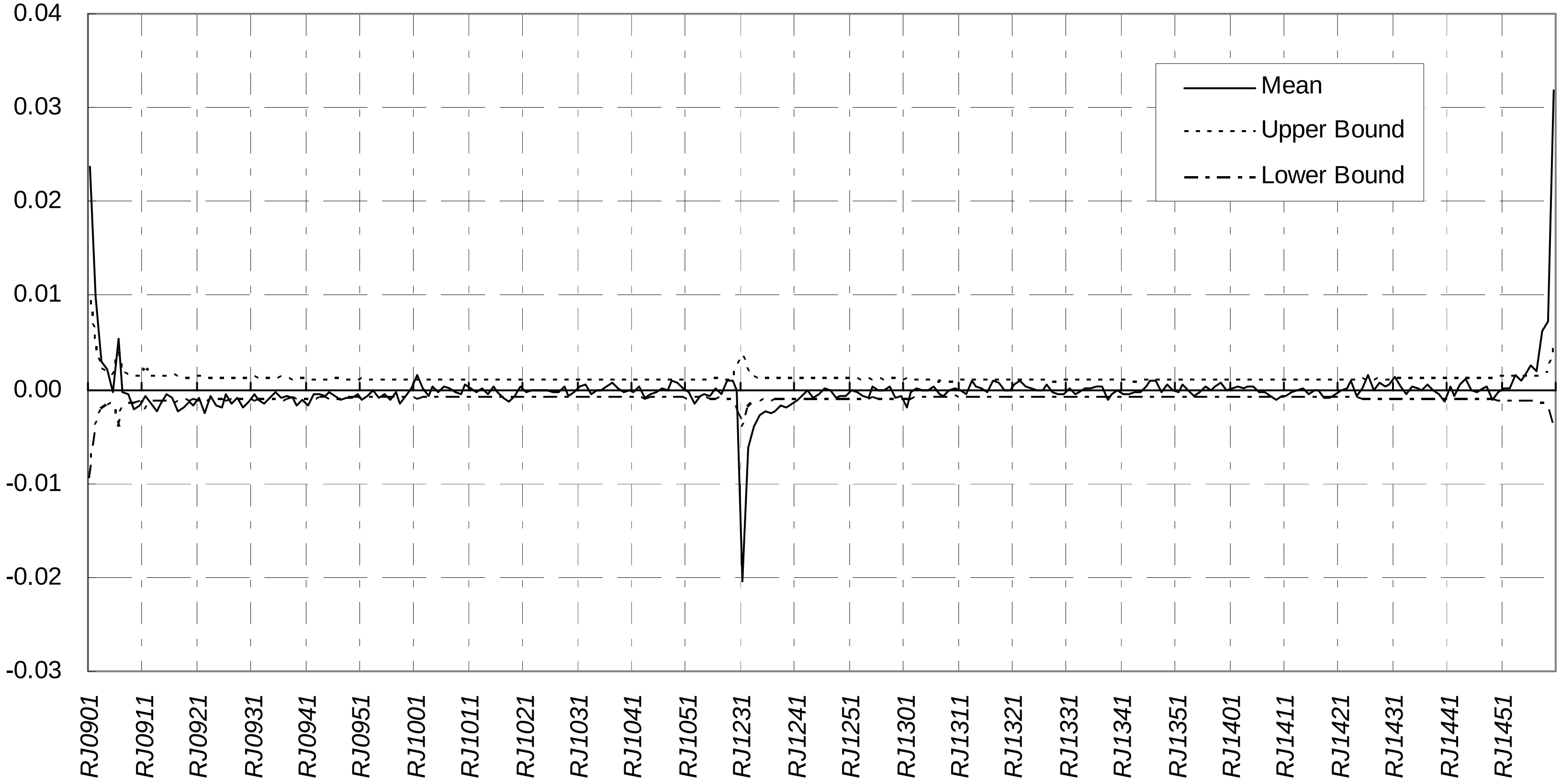
Notes: See notes to Table V for definition of the variables. *P*-values of the *F* tests are shown in the Table. 'A vs. B'. Deaton's *F* test takes Model A as given and inserts additional variables that appear in Model B. If the *F* test of these variables is not significant, these variables from Model B do not have additional explanatory power, which implies a rejection of Model B. In our tests, only a single variable is added at a time, thus the *F* test is equivalent to a *t* test. 'B vs. A' reverses the procedure. '10% signif.' stands for the number of cases, out of seven trials, that the alternative variable is significant at a 10% level. '5% signif.' is the same proportion at a 5% level. There are four pairs of Model A and B above: *RUOC* vs. *RUCC*, *RUCO* vs. *RUCC*, *RUMN* vs. *RUCC*, and *RUAN* vs. *RUCC*. Each row represents a regression equation explaining the variable indicated by the first column.

Table X. Explanatory Power of *RJCC* and Other Returns: Deaton's *F*-tests

	A vs. B *RJOC*	B vs. A *RJCC*	A vs. B *RJ0901*	B vs. A *RJCC*	A vs. B *RJMN*	B vs. A *RJCC*	A vs. B *RJAN*	B vs. A *RJCC*
RU0931	0.00472	0.00000	0.00394	0.00000	0.44871	0.00000	0.51410	0.00000
RU0932	0.00000	0.00010	0.00000	0.00000	0.72998	0.01032	0.02049	0.01891
RU0933	0.00453	0.01070	0.00456	0.03588	0.74912	0.42705	0.09318	0.77480
RU0934	0.00172	0.00004	0.00177	0.02522	0.07548	0.00005	0.87920	0.00064
RU0935	0.59814	0.92552	0.59639	0.08288	0.43153	0.10340	0.32860	0.45676
RU0936	0.28287	0.49688	0.28345	0.07164	0.85631	0.43532	0.61764	0.34584
RU0937	0.05003	0.11015	0.05798	0.04696	0.74770	0.63248	0.51200	0.54707
RU0938	0.76636	0.22761	0.74273	0.00234	0.38694	0.00334	0.48720	0.00954
RU0939	0.05066	0.00204	0.05160	0.00138	0.98512	0.00370	0.32141	0.00001
RU0940	0.72722	0.86757	0.71209	0.05153	0.26335	0.03348	0.25197	0.32873
RU0941	0.81075	0.80163	0.82333	0.07280	0.47568	0.54970	0.55143	0.05257
RU0942	0.21232	0.39997	0.23473	0.06137	0.94958	0.42265	0.55186	0.42460
RU0943	0.56989	0.23213	0.57402	0.04912	0.35734	0.02402	0.55752	0.08851
RU0944	0.68715	0.09798	0.68856	0.00003	0.68121	0.00092	0.91463	0.00007
RU0945	0.35454	0.20199	0.33749	0.40006	0.64717	0.21135	0.97990	0.22655
10% signif.	6	6	6	14	1	8	2	8
5% signif.	4	5	4	9	0	8	1	6

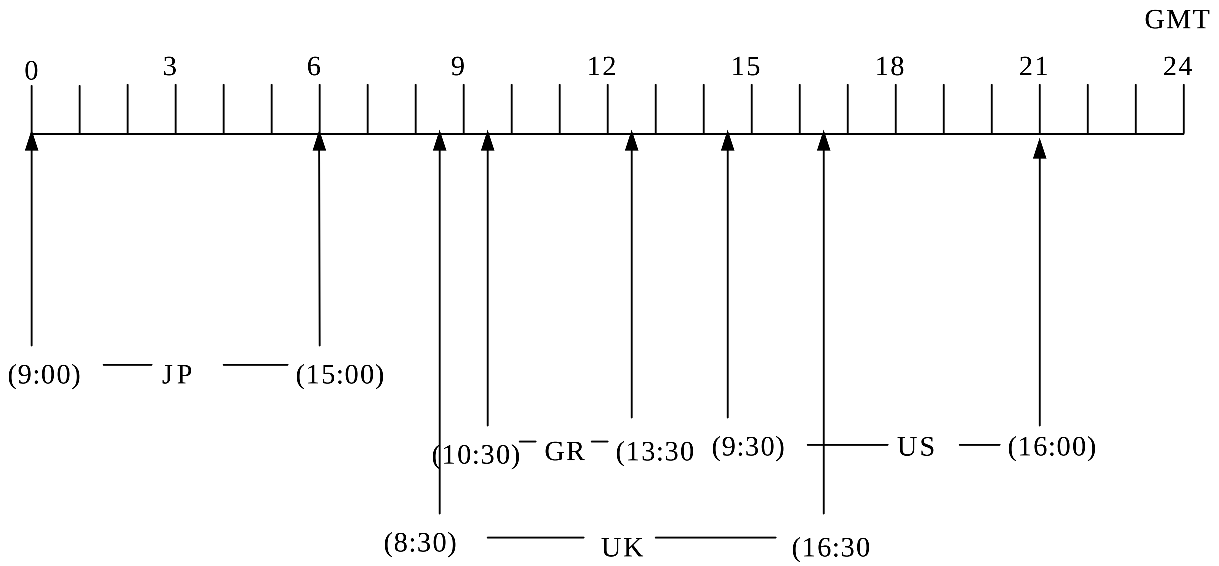
Notes: See notes to Table I for definition of the variables. *P*-values of the *F* tests are shown in the Table. For the test procedure, see notes to Table IX. '10% signif.' stands for the number of cases, out of fifteen trials, that the alternative variable is significant at a 10% level. '5% signif.' is the same based on a 5% level. There are four pairs of Model A and B above: *RJOC* vs. *RJCC*, *RJ0901* vs. *RJCC*, *RJMN* vs. *RJCC*, and *RJAN* vs. *RJCC*. Each row represents a regression equation explaining the variable indicated by the first column.

Figure 1 Daily Averages of TOPIX One-Minute Returns



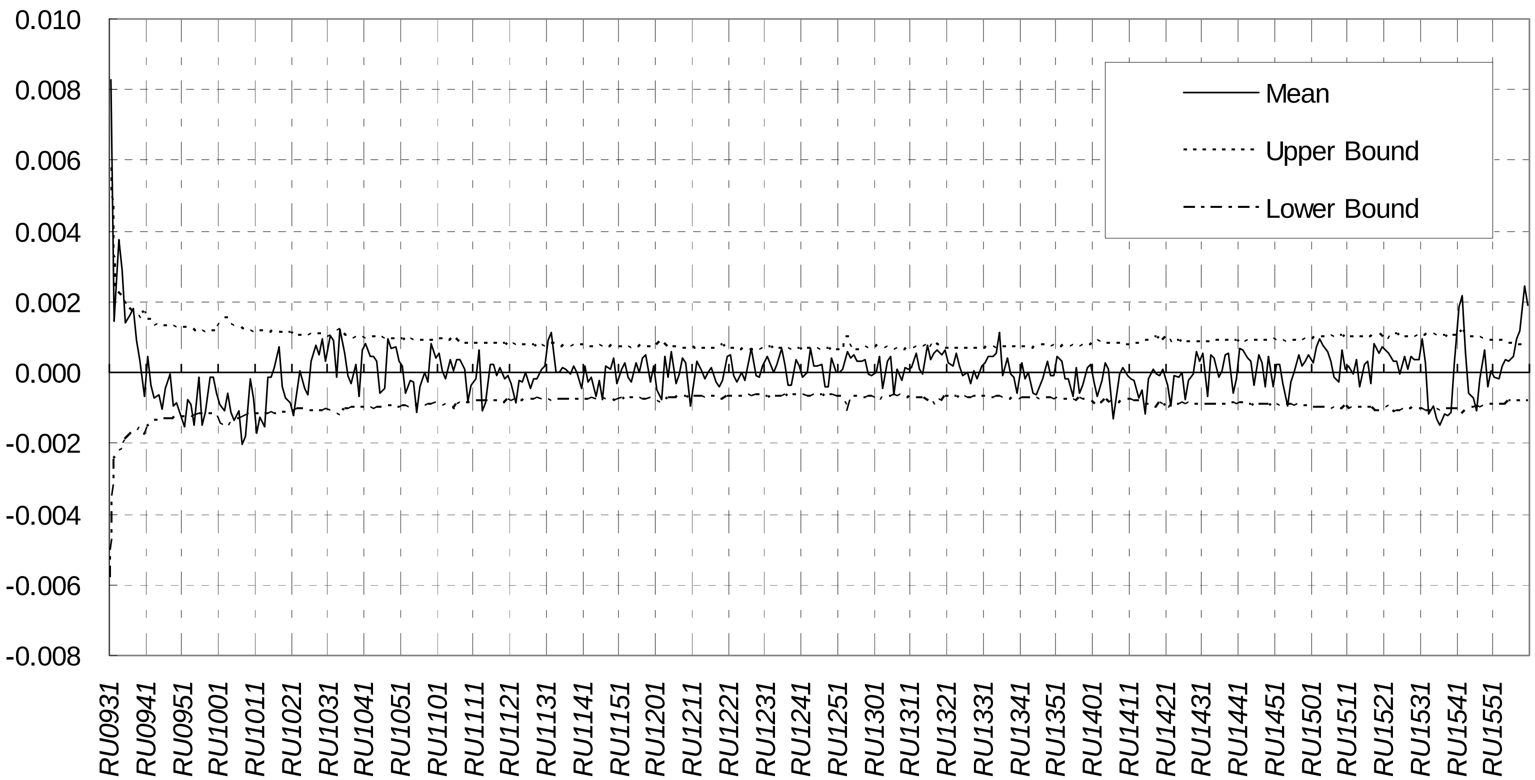
Notes: One-minute returns of TOPIX are averaged across days. The sample period is from January 5, 1988 to November 27, 2003. The sample size varies between 3,080 and 3,946. See Table I for the differing sample sizes. 95% confidence bands are shown for the null of a zero mean.

Figure 2 Opening and Closing Times of the Four Markets



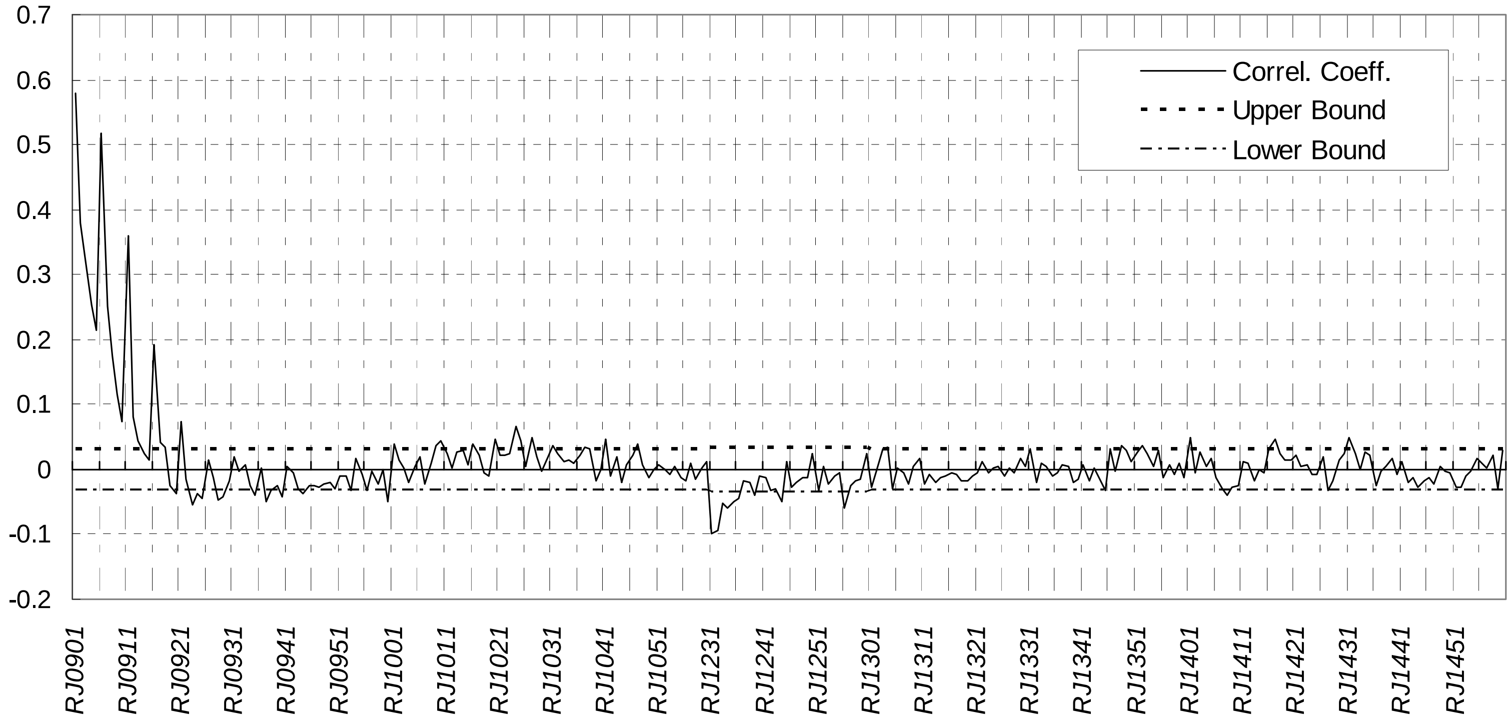
Notes: GMT stands for Greenwich Mean Time. Local time is in parentheses. JP, GR, UK, and US stand for the Tokyo, Frankfurt, London, and New York Stock Exchanges, respectively.

Figure 3 Daily Averages of S&P500 One-Minute Returns



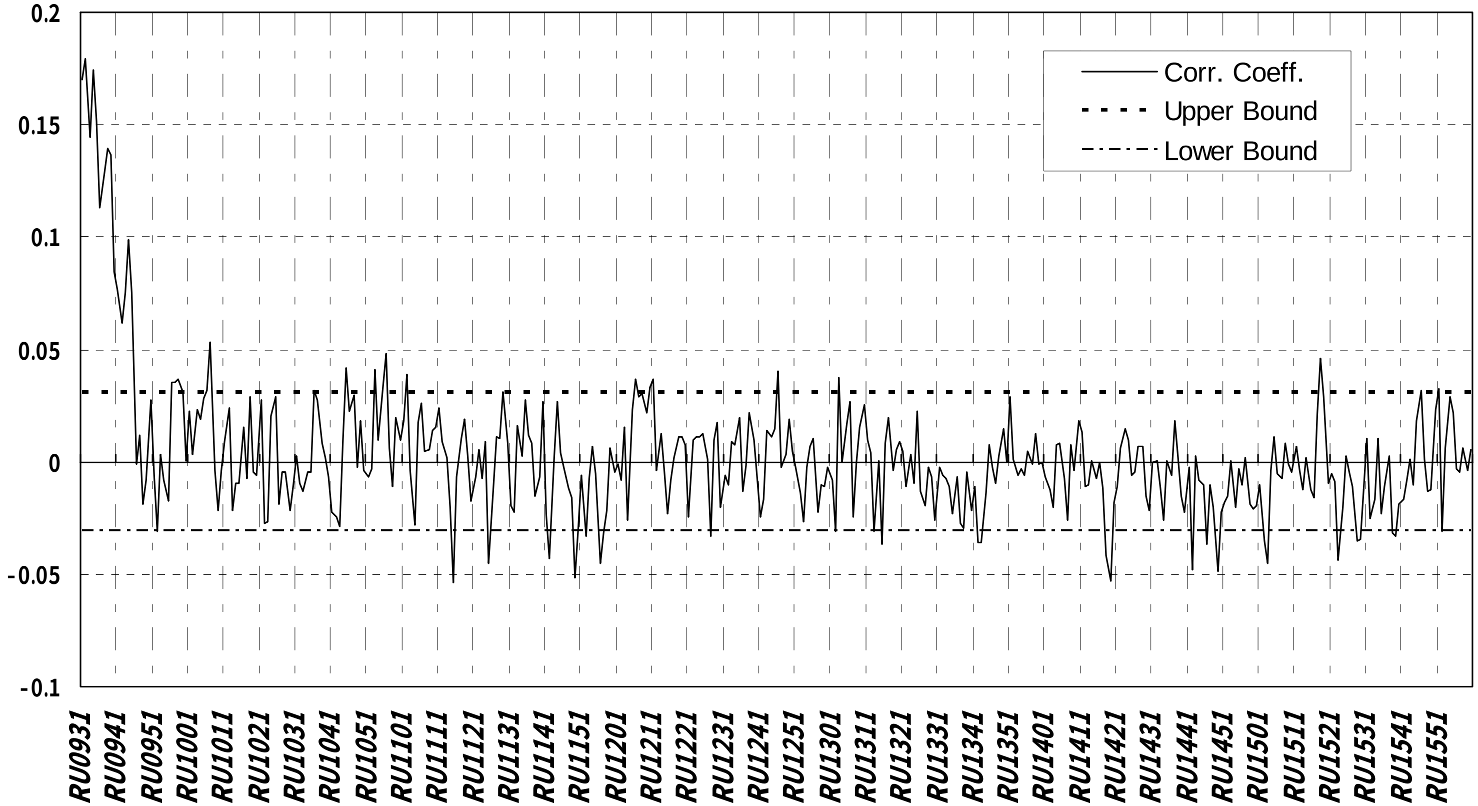
Notes: One-minute returns of S&P500 are averaged across days. The sample period is from January 5, 1988 to November 27, 2003. The sample size is 4014. 95% confidence bands are shown for the null of a zero mean.

Figure 4 Correlation Coefficient of TOPIX 1 Min-Returns
with Previous Day's Close-to-Close Daily Return of S&P500 (RUCC)



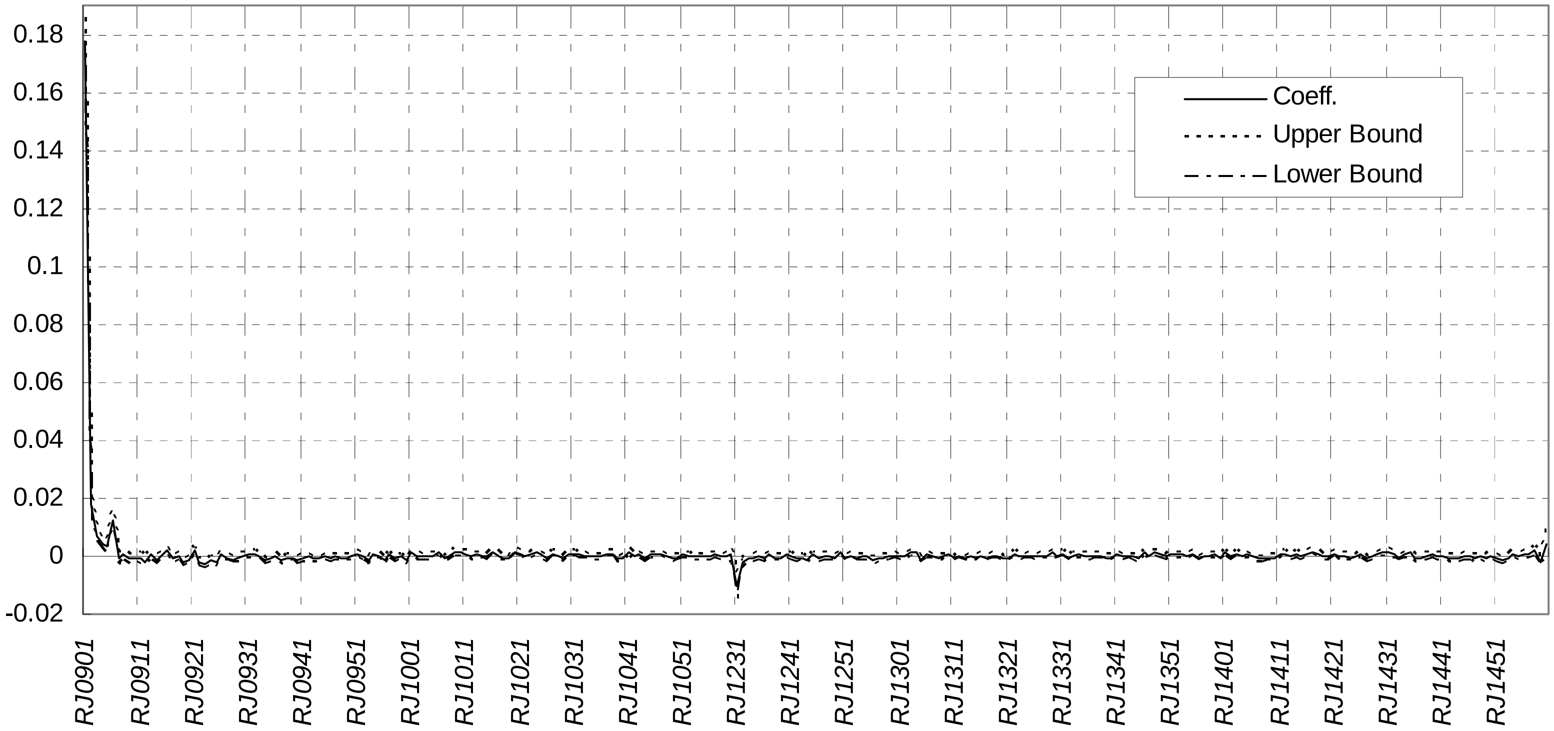
Notes: *RJhhmm*, where *hhmm* is the hours and minutes of the time of day, is the one-minute return of TOPIX. Notice there is a lunch break between 11:00 and 12:30. Correlation coefficients between each of *RJhhmm* and $RUCC_{t-1}$ (previous day's close-to-close daily return of S&P500) are plotted. The sample period is from January 5, 1988 to November 27, 2003. The sample size is 3080 for the half-hour duration from 12:31 to 13:00 due to a longer lunch break before April 26, 1991 and is between 3891 and 3946 for other times. See Footnote 12 for description of this difference in the sample size. Upper and lower bounds indicate 95% confidence bands for the null of a zero correlation coefficient.

Figure 5 Corrrelation Coefficient of S&P500 1-Min. Returns with Previous Day's Close-to-Close Daily Return of TOPIX (RJCC)



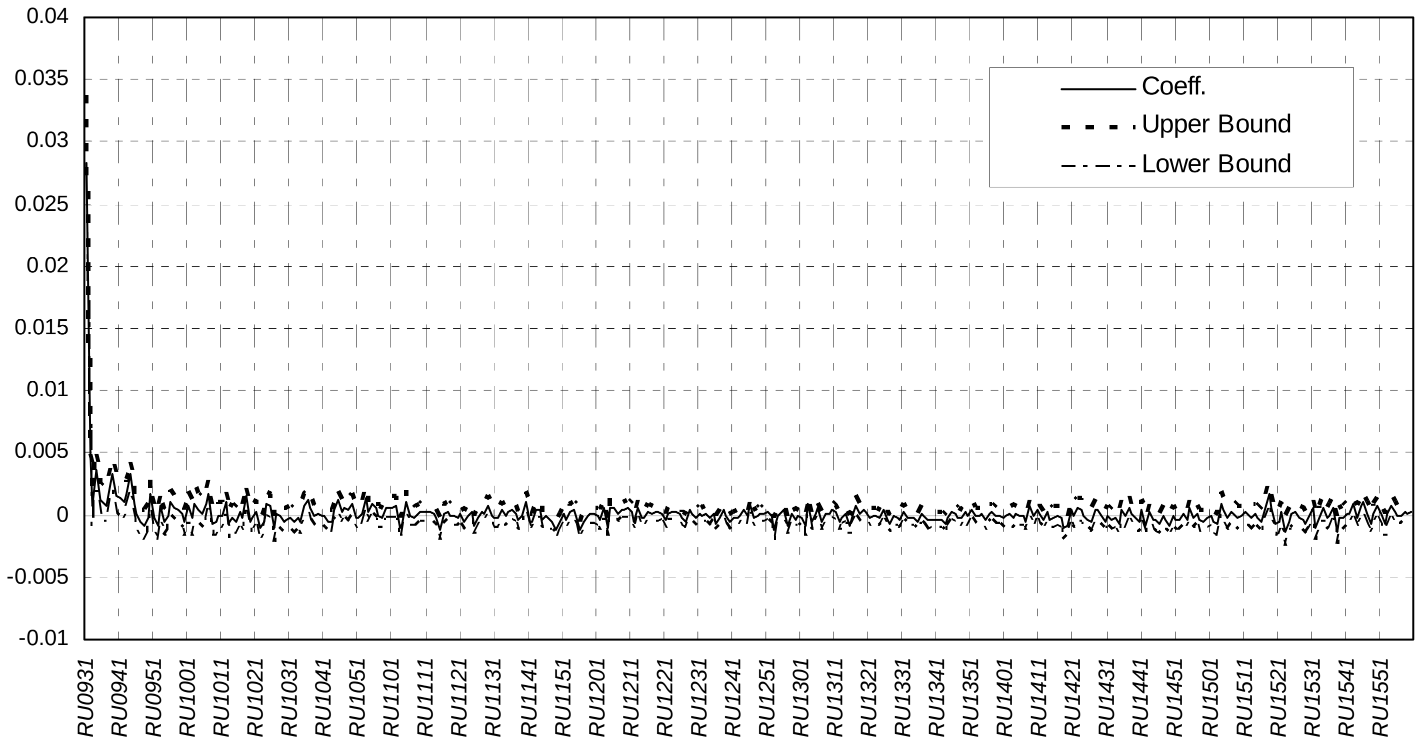
Note: *RUhhmm*, where *hhmm* is the hours and minutes of the time of day, is the one-minute return of S&P500. Correlation coefficients between each of *RUhhmm* and $RJCC_t$ (previously observed close-to-close daily return of TOPIX) are plotted. The sample period is from January 5, 1988 to November 27, 2003. The sample size is 4014. Upper and lower bounds indicate 95% confidence bands for the null of a zero correlation coefficient.

Figure 6 Regression Coefficients on *RUCC*



Note: This plots regression coefficients on $RUCC_{t\text{-}1}$ of equation (3), $RJhhmm_t = \alpha_{hhmm} + \sum_{i=1}^{5} \beta_{hhmm}^{i} RJ(hhmm - i)_t + \gamma_{hhmm} RJhhmm_{t-1} + \delta_{hhmm} RUCC_{t-1} + u_t$, and their 95% confidence bands. They capture the effect of previous day's close-to-close return of S&P500 on each of the TOPIX one-minute returns. See notes to Figure 4.

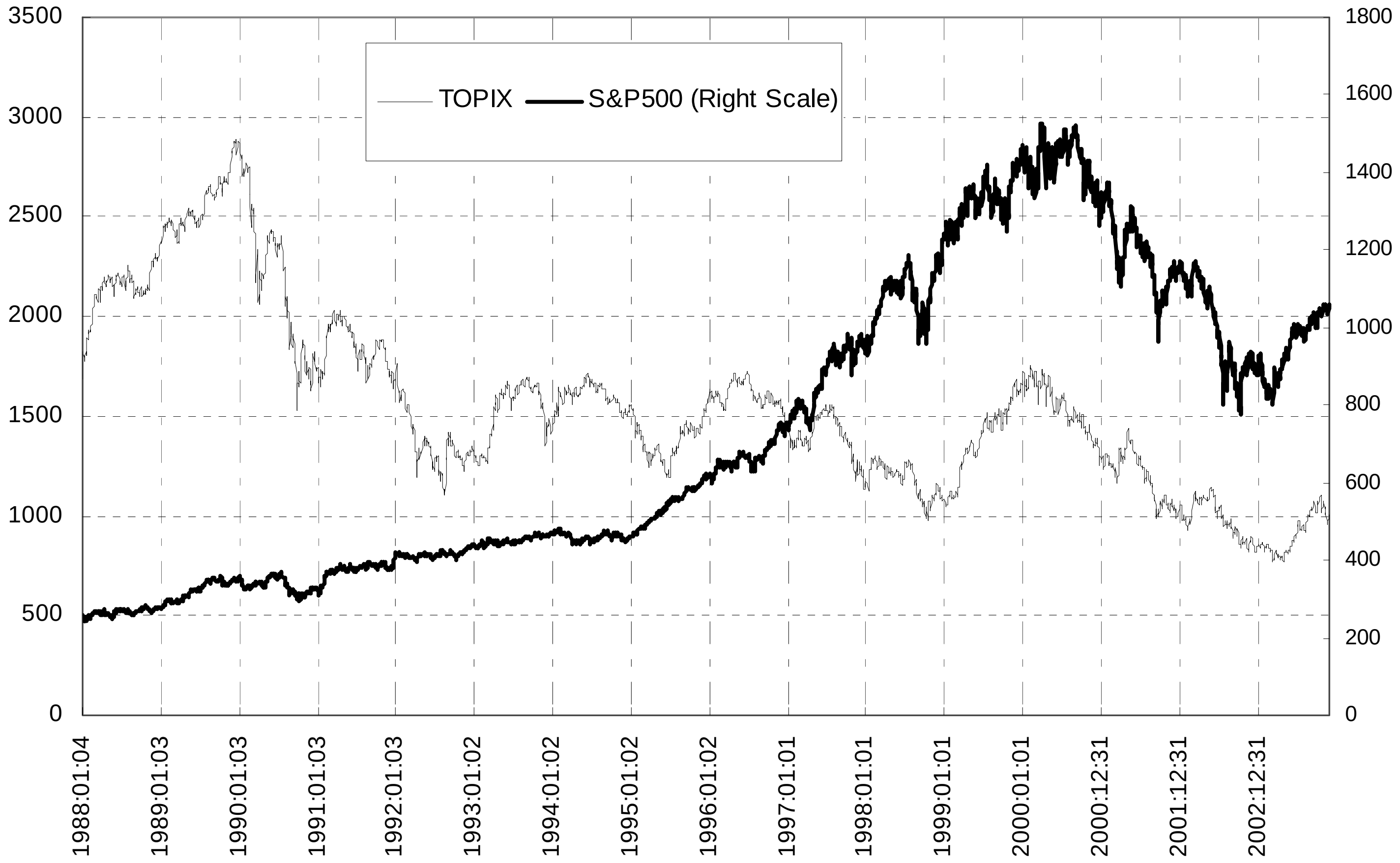
Figure 7 Regression Coefficients on RJCC



Note: This plots regression coefficients on $RJCC_t$ of equation (4) $RUhhmm_t = \alpha_{hhmm} + \sum_{i=1}^{3} \beta^i_{hhmm} RU(hhmm - i)_t + \gamma_{hhmm} RUhhmm_{t-1} + \delta_{hhmm} RJCC_t + u_t$,

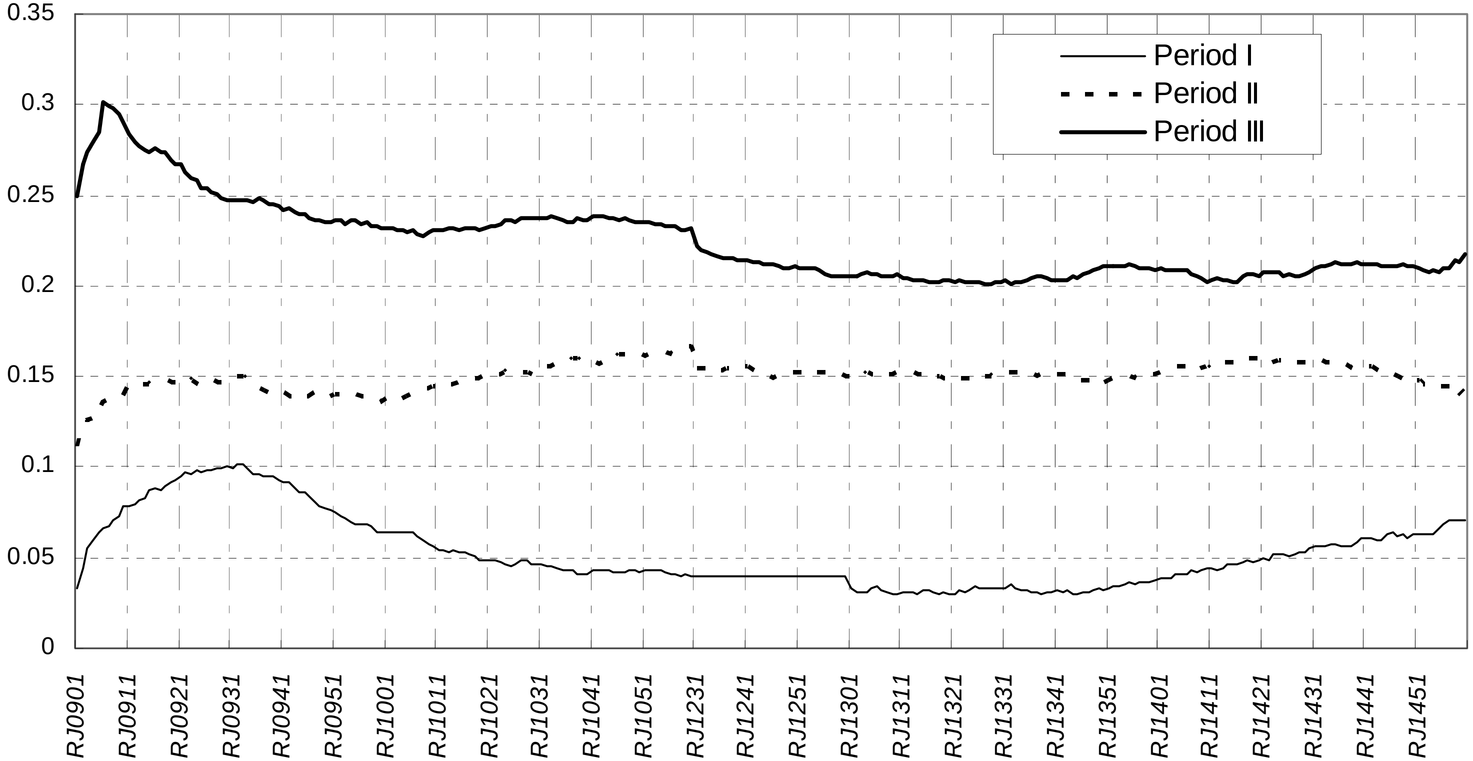
and their 95% confidence bands. They represent effects of the preceding close-to-close daily return of TOPIX on each one-minute return of S&P500. See notes to Figure 5.

Figure 8 Daily Closing Values of S&P500 and TOPIX



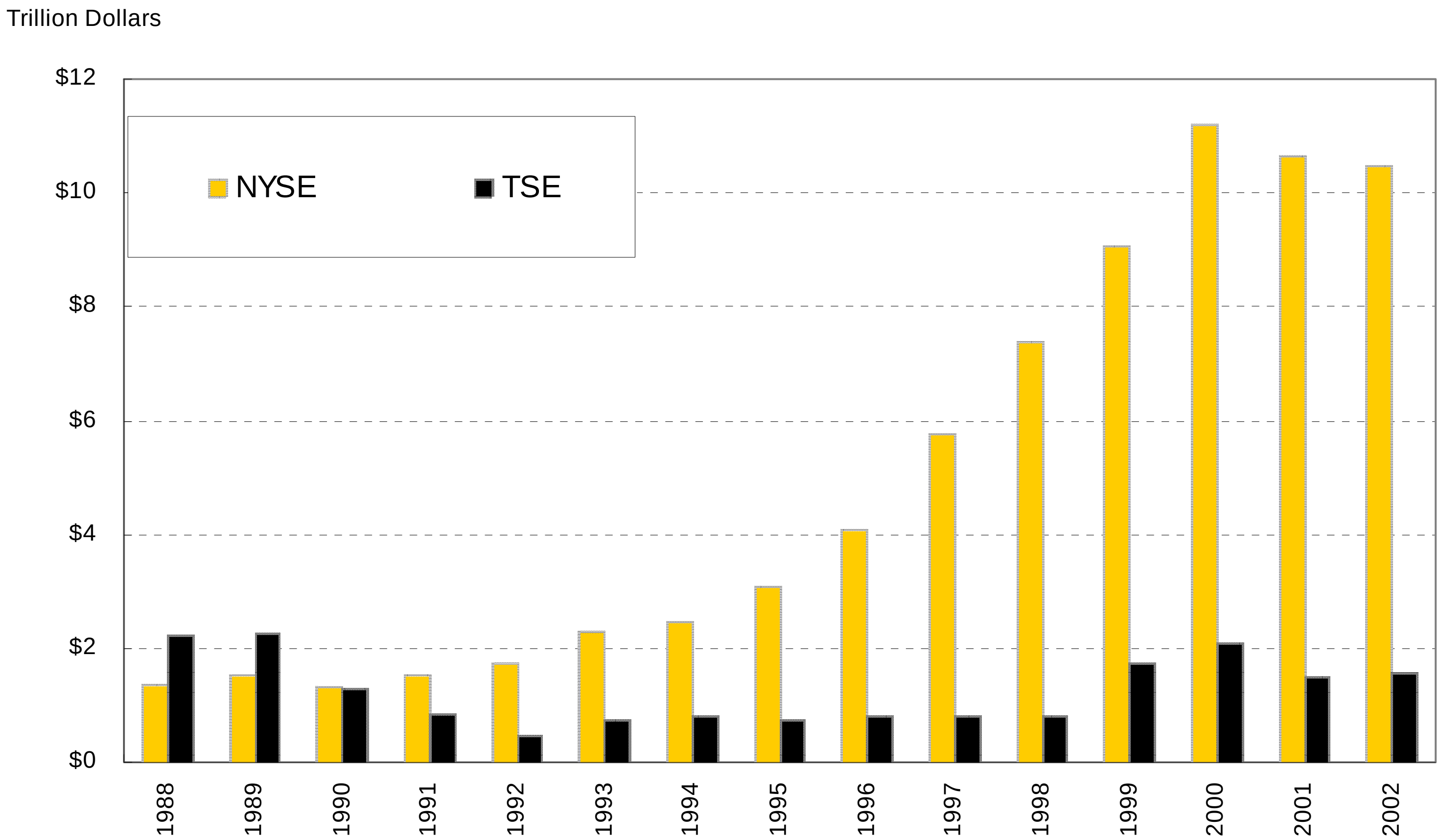
Note: Daily closing values are from TickData.com and the TSE.

Figure 9 Cumulative Sum of Regression Coefficients on *RUCC*: Three Subperiods



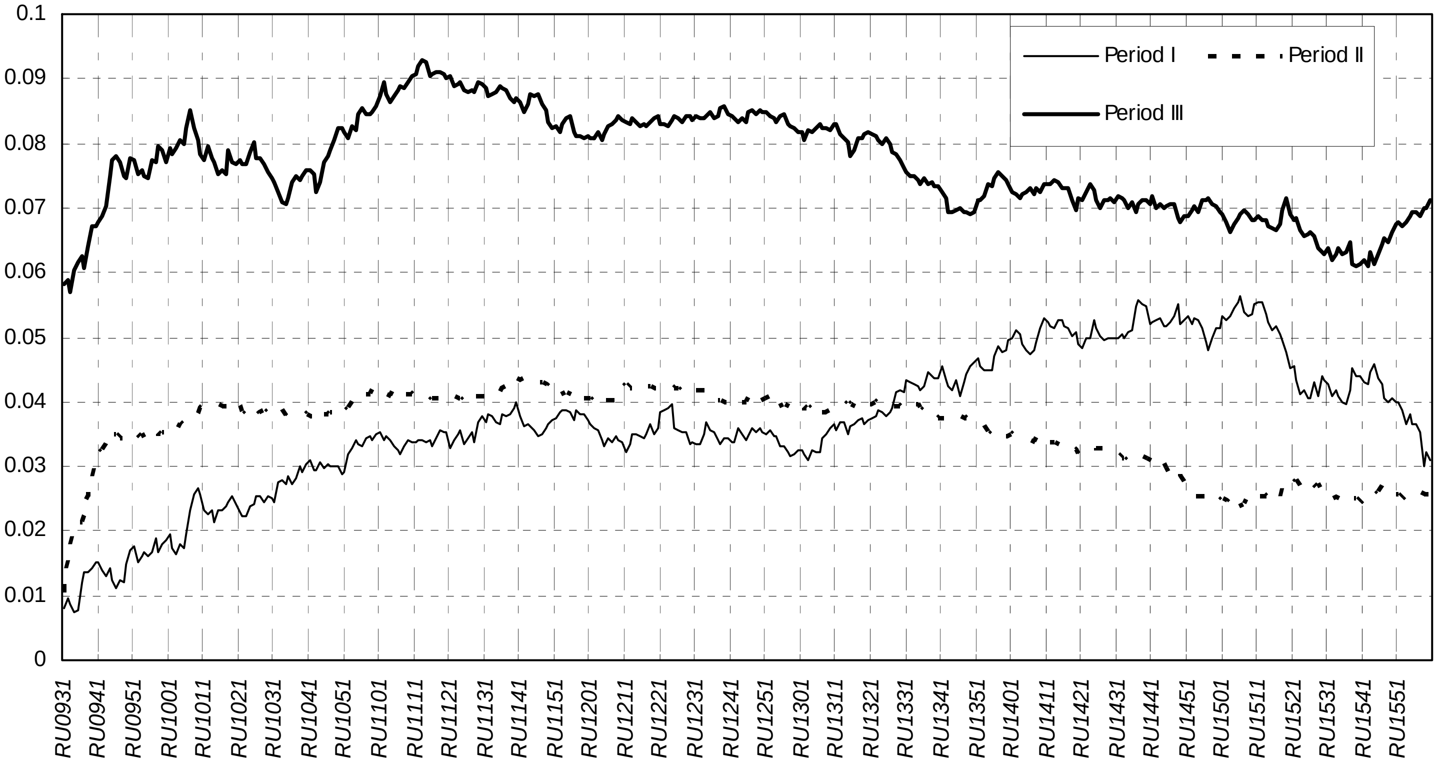
Note: Each line is a cumulative sum of regression coefficients on $RUCC_{t-1}$ for three subperiods. Period I is from January 5, 1988 to December 21, 1989, Period II from January 4, 1990 to October 15, 1998, Period III from Oct. 16, 1998 to November 27, 2003. Notice that there do not actually exist regressions for *RJ1231*, …, *RJ1300* for Period I because the lunch break was from 11:00 to 13:00 before April 26, 1991.

Figure 10 Annual Turnover of NYSE and TSE



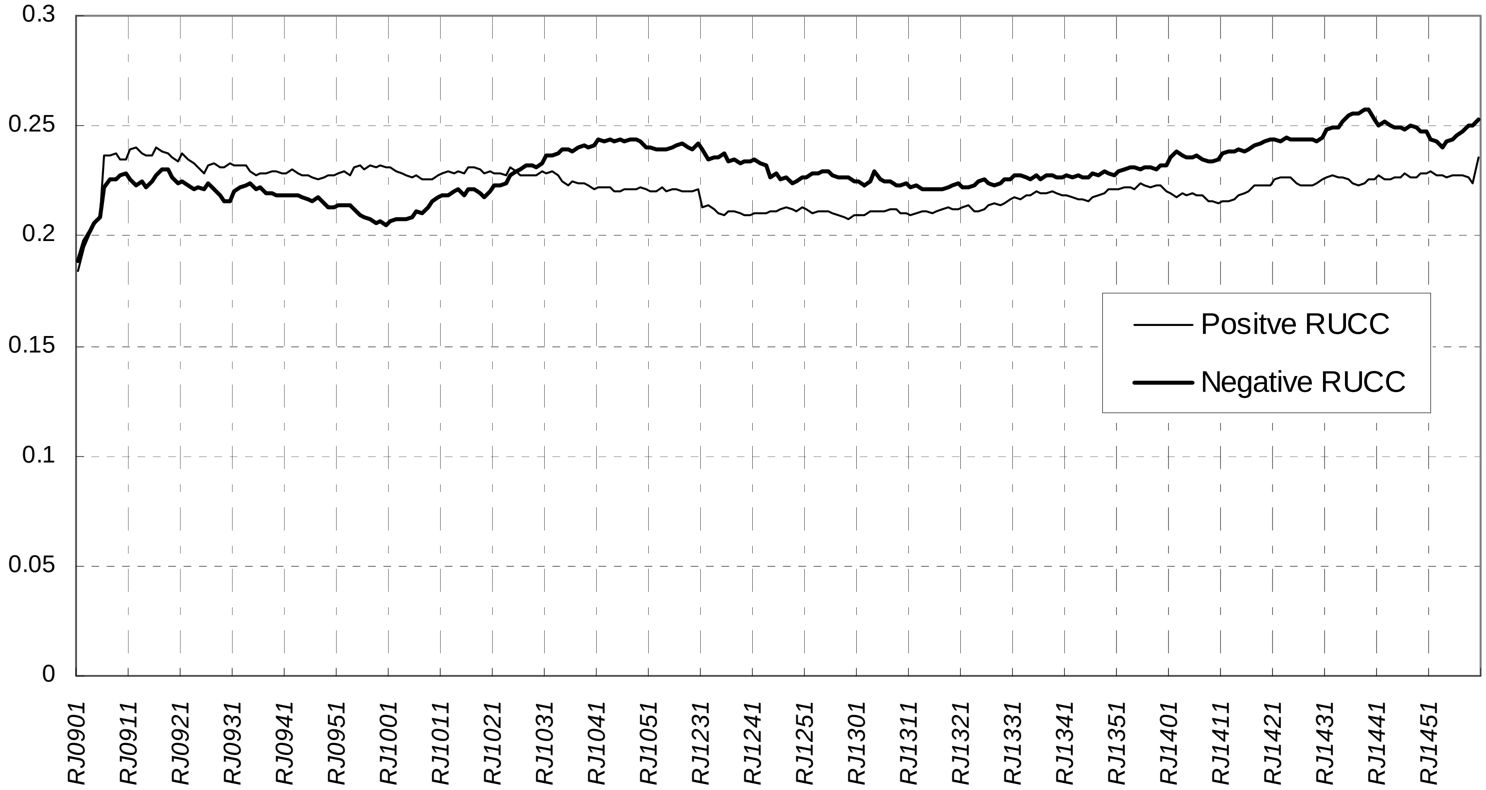
Note: The data source is the respective Stock Exchanges. The value of the TSE is converted into US dollars using annual average yen/dollar rate retrieved from the IMF *International Financial Statistics* CD-ROM.

Figure 11 Cumulative Sum of Regression Coefficients on RJCC: Three Subperiods



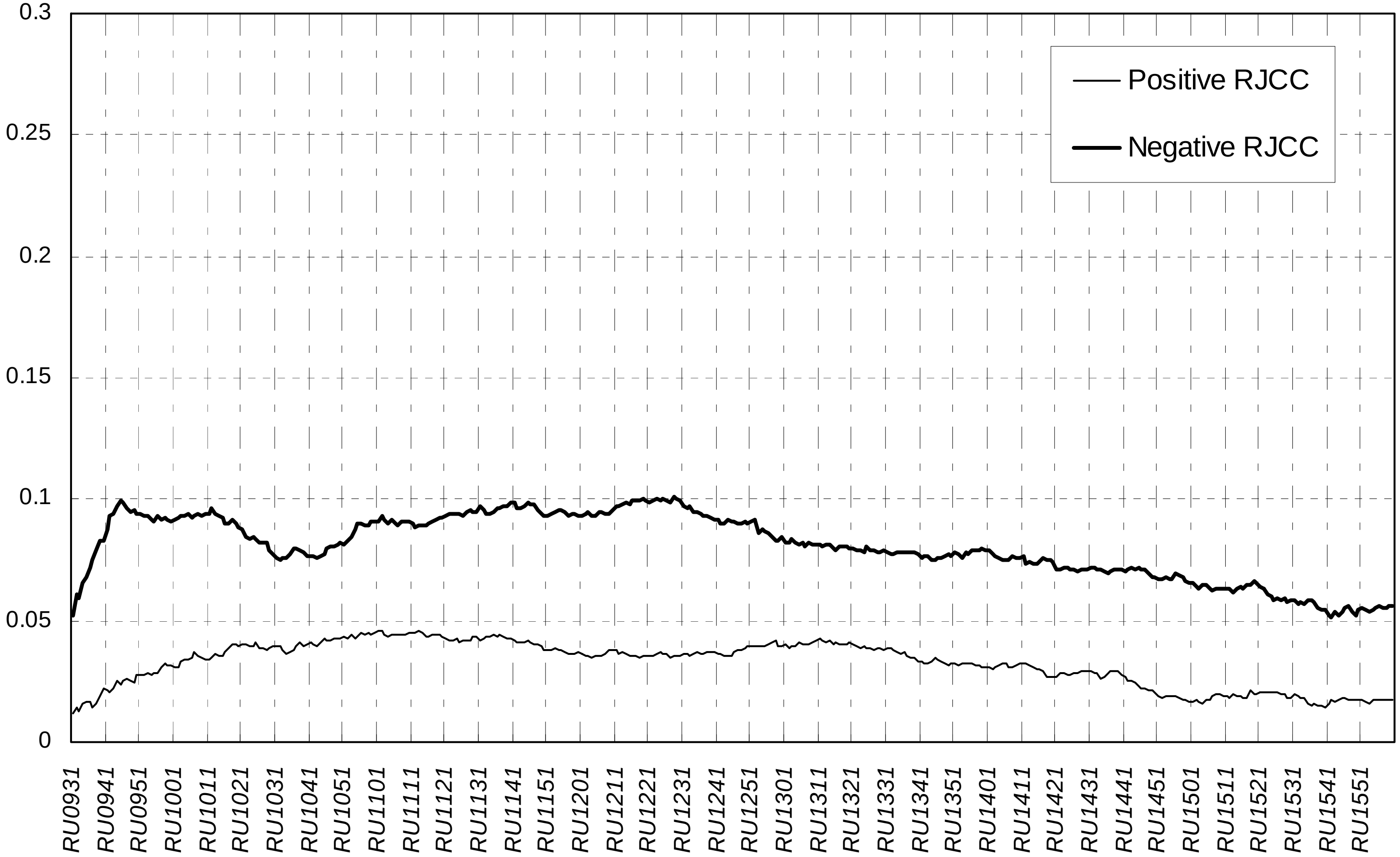
Note: Each line is a cumulative sum of regression coefficients on $RJCC_t$ in equation (4) for three subperiods. See also notes to Figure 8.

Figure 12 Cumulative Sum of Regression Coefficients on Positive and Negative RUCC



Note: Regression equation (3) is estimated separately for positive and negative $RUCC_{t\text{-}1}$.

Figure 13 Cumulative Sum of Regression Coefficients on Positive and Negative RJCC



Note: Regression equation (4) is estimated separately for positive and negative $RJCC_t$.