



The Federal funds market and the overnight Eurodollar market

Young-Sook Lee *

School of Economics, University of Nottingham, University Park, Nottingham NG7 2RD, UK

Received 10 November 2000; accepted 31 October 2001

Abstract

This paper investigates the effect of daily management of Federal Reserve accounts by US depository institutions on the interest rate outside the US. Spindt and Hoffmeister (*Journal of Financial and Quantitative Analysis* 23 (1988) 401), Griffiths and Winters (*Journal of Banking and Finance* 19 (1995) 1265) and Hamilton (*Journal of Political Economy* 104 (1996) 22) found that the Fed funds rate exhibited calendar day effects caused by Federal Reserve regulations. I find that the overnight Eurodollar rate shows similar predictable daily changes as does the Fed funds rate although the absolute magnitudes are slightly less. The empirical results support the hypothesis that the tendencies in daily changes in the two overnight interest rates are caused by the characteristics of the Fed funds market.

© 2003 Elsevier Science B.V. All rights reserved.

JEL classification: E44; G21

Keywords: Overnight Eurodollar rate; Fed funds rate; Calendar day effect; Federal Reserve regulations

1. Introduction

The purpose of this paper is to investigate the effect of daily management of Federal Reserve accounts by US depository institutions on interest rates outside the US. Previous research (Campbell, 1987; Saunders and Urich, 1988; Spindt and Hoffmeister, 1988; Griffiths and Winters, 1995; Hamilton, 1996) showed predictable patterns in the Fed funds rate caused by Federal Reserve regulations. Hamilton (1996) found

* Tel.: +44-115-846-6715; fax: +44-115-951-4159.

E-mail address: young-sook.lee@nottingham.ac.uk (Y.-S. Lee).

that over the period 1984–1990 the Fed funds rate tended to fall during the reserve maintenance period until the second Friday, decrease on Fridays and before US holidays but increase on Mondays and surge upwards on settlement Wednesdays and after holidays. The variance of the Fed funds rate increased toward the end of a settlement period and was highest on settlement Wednesdays. These results are similar to the findings of Griffiths and Winters (1995). These authors claim that these features are the result of reserve requirements and the characteristics of the Fed funds market.

To explore the relationships between external (Eurocurrency or offshore) and internal (domestic) money market interest rates, previous research studied the Granger causality between Eurodollar rates and US domestic interest rates on compatible assets. Reinhart and Harmon (1987) examined the relationship between the daily Fed funds rate and the daily overnight Eurodollar rate. They studied the effect of the switch from next-day settlement to same-day settlement for Eurodollar deposits in October 1981. They showed that this change caused a structural shift in the causal relationship between the two markets. They argued that the Fed funds rate was not Granger caused by the overnight Eurodollar rate but the overnight Eurodollar rate was Granger caused by the Fed funds rate during the next-day settlement period. The overnight Eurodollar rate and the Fed funds rate Granger caused each other during the same-day settlement period. Other early studies (Hendershott, 1967; Kwack, 1971; Levin, 1974; Kaen and Hachey, 1983) showed that US interest rates were not Granger caused by Eurodollar rates but Eurodollar rates were Granger caused by US domestic interest rates. However, more recent studies (Fung and Isberg, 1992; Fung and Lo, 1995) found that Eurodollar rates and US domestic interest rates Granger caused each other after the middle of the 1980s, with weaker feedback from Eurodollar rates to US domestic interest rates. These results are used as indicators of whether interest rate innovations originated primarily in the US market or in the Eurodollar market. However, the Eurodollar and US domestic interest rates are, in general, measured at different times within the same day so it is hard to interpret their results as a Granger-causality test. Yesterday's Fed funds rate, for example, reflects more recent information than yesterday's Eurodollar rates in London and, therefore, should help forecast today's Eurodollar rate regardless of the direction of causation.

This paper analyzes the Fed funds rate and the overnight Eurodollar rate between 1984 and 1997 to examine the pervasiveness of Federal Reserve Board regulations governing required reserves in the money market outside the US. The main focus is to see whether the overnight Eurodollar rate showed the same calendar day effects as the Fed funds rate. In contrast to previous research on the Eurodollar rate, this study allows for outliers and GARCH effects. The overnight Eurodollar rate exhibits very similar calendar day effects as the Fed funds rate, but the absolute magnitudes are slightly smaller. These results support the hypothesis that the calendar day effects of the Fed funds rate and the overnight Eurodollar rate are created by Federal Reserve regulations of the reserve settlement process and the characteristics of the Fed funds market. The differential between the Fed funds rate and the overnight Eurodollar rate is predictable and positively serially correlated. A US bank could have

made a small arbitrage profit by using the predictability of the differential between two overnight interest rates. This small arbitrage opportunity indicates that factors other than interest rates have prevented perfect market integration of the Fed funds market with the overnight Eurodollar market.

The paper proceeds as follows. Section 2 briefly describes the institutional details and characteristics of the Eurodollar market and the Fed funds market in the US. Section 3 describes the data and Section 4 develops the empirical setting. The empirical results are reported in Section 5. Section 6 concludes.

2. The Eurodollar market and the Fed funds market

A US bank or other depository institution has to satisfy reserve requirements, the percentage of deposits that they may not lend out or invest, which must be held either as vault cash or on deposit at a Federal Reserve Bank. To get desired reserves, a bank has several options. It can purchase (sell) Federal funds, borrow from the Fed through the discount window, sell (buy) Eurodollars, sell (buy) securities under repurchase agreements (reverse repurchase agreements) or sell (buy) large certificates of deposit.

Eurodollars are US dollar-denominated deposit liabilities of the Eurodollar market, which is an international telephone and telex network located in many countries outside the US. The Eurodollar market is a wholesale market. Commercial and central banks, large corporations, and governments are the major customers. However, banks that participate in the Eurodollar market actively borrow and lend Eurodollars among themselves and interbank transactions alone have made up over 60% of the total volume of transactions over the 1980s and 1990s.

The Fed funds market is the interbank market for overnight lending of funds on deposit in a bank's reserve account at the Fed. Most Fed funds transactions are overnight loans between two depository institutions. It has been primarily made up of domestic commercial banks, thrift institutions, agencies and branches of foreign banks, Federal agencies, and government securities dealers in the US. The Federal Reserve does not pay interest on reserve accounts so banks have an incentive to minimize balances and to lend beyond their required (or desired) excess reserves.

To satisfy the reserve requirements, the average daily level of reserves during the two-week maintenance period must equal or exceed the average required reserves during the two-week computation period. Panels A, B and C of Fig. 1 indicate the reserve accounting system from 1984 to 1998. Since 1984, the maintenance period over which reserves must be held is a two-week period beginning on a Thursday and ending on a Wednesday. The last Wednesday of the maintenance period is called settlement Wednesday. The computation period is a two-week period for computing the average required reserves on the basis of daily average balances of deposits. Reserves required against transaction deposits are computed against the average end-of-day transaction deposits at the bank during the computation period. The computation period against transaction deposits began on a Tuesday and ended on a Monday two days before the end of the reserve maintenance period. The computation

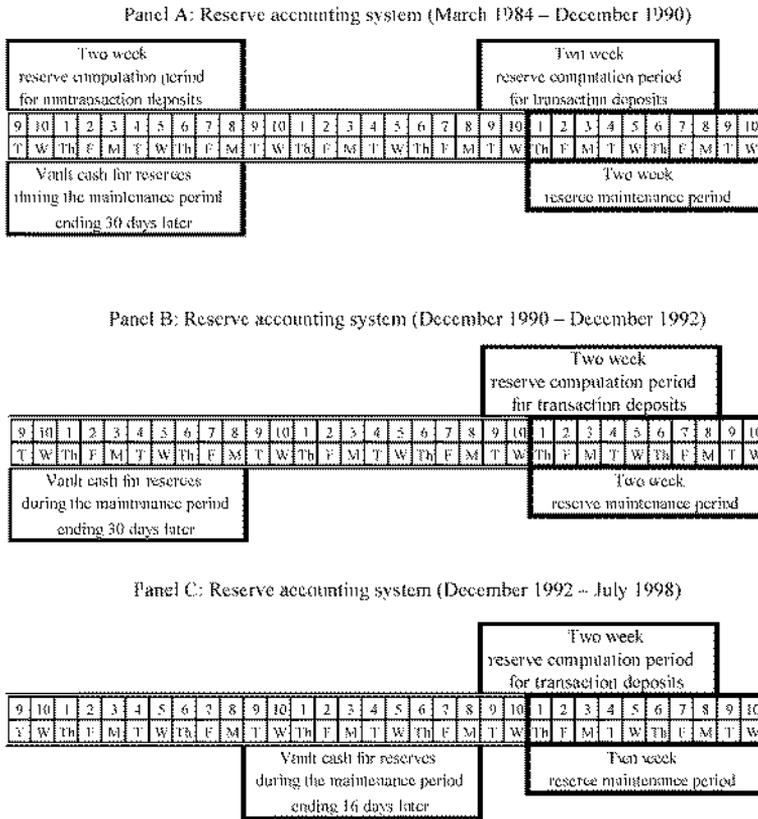


Fig. 1. Reserve accounting system, 1984:03–1998:07. Panels A, B, and C display the US reserve accounting system from March 1984 to December 1990, from December 1990 to December 1992 and from December 1992 to July 1998 respectively. A reserve maintenance period is a two-week period over which depository institutions are required to maintain reserve funds on account with the Federal reserve. The numbers, 1, 2, . . . , 10 indicate which day of a two-week reserve maintenance period day t falls on. For example, 1 denotes the first Thursday of a maintenance period; 2 denotes the first Friday of a maintenance period; 10 denotes the second Wednesday of a maintenance period. The computation period is a two-week period for computing the average required reserve on the basis of daily deposit liabilities.

period was amended in July 1998 and since then it has ended three days before the beginning of the maintenance period. For required reserves against non-transaction deposits, the computation period was also a two-week period ending two weeks prior to the beginning of the reserve computation period for transaction deposits until 1990. To calculate a bank’s average reserves, the Fed added the average of a bank’s deposit at the Federal Reserve during the reserve maintenance period to the average daily vault cash during a two-week period as shown in Fig. 1. The total deposits are calculated by adding deposits for each calendar day over the computation period. The deposits on Friday are multiplied by three or, if the next Monday is a one-day holiday, multiplied by four, as directed by the weekend accounting conventions.

A bank did not know the amount of reserve requirements against transaction deposits and the amount of reserve balances at the Fed until late in the maintenance period. Therefore, the bank needed to estimate them within the maintenance period until July 1998. A US bank could vary the amount of its reserves to meet the reserve requirements on the settlement Wednesday when information on actual deposits was available and, therefore, the settlement Wednesday was very important to all banks.

Transaction deposits had been subject to the 3% reserve requirement for the first \$25–50 million and 12% for amounts exceeding this during the period from 1984 to 1997. US banks had been required to keep 3% reserves on Eurocurrency borrowing in excess of their funds abroad. It was changed to 0% in 1990.

Because Fed funds and Eurodollars transactions are usually unsecured by anything other than verbal agreements, a bank limits the size of transactions for each buyer to minimize the seller's exposure to default risk. A bank with poor credit might be unable to buy Federal funds or Eurodollars.

The Fed funds market has wide access to all banks. The top Fed funds brokers also broker Eurodollars and speak to a wide range of banks including the majority of the large and medium-sized banks. The characteristics of dollar-denominated assets and liabilities in the Fed funds market and the overnight Eurodollar market are nearly identical and the two overnight funds could be close substitutes.

3. Description of data

The data set used in this study consists of the daily Fed funds rate and the daily overnight Eurodollar rate, quoted at an annual rate and provided by the Federal Reserve Board. For the Fed funds rate, I use the effective Fed funds rate, which is a weighted average of the funds rates that prevailed during the day, where the weights used are the amount of funds that are traded at each of the funds rates that prevailed. The overnight Eurodollar best deposit rate in London between 12:00 a.m. and 1:00 p.m. Greenwich Mean Time,¹ which corresponds to 7:00 and 8:00 a.m. Eastern Standard Time (EST), is used for the daily overnight Eurodollar rate.

The sample period is from March 1, 1984 to March 26, 1997 (from the first day of a maintenance period to the last day of a maintenance period). After excluding

¹ The practice of accepting US dollar-denominated deposits outside of the US began in Europe and has spread to several Caribbean islands, Hong Kong, Tokyo, Singapore, the International Banking Facilities in the US and other financial centers. The largest center for Eurodollar activity is London. The various branches of a bank located in London, Paris and elsewhere usually offer the same interest rates on Eurodollars. A US bank would not find it worthwhile to pay a higher interest rate on a London dollar deposit than on a Paris dollar deposit if the funds are to be used to finance a purchase of a loan in New York. Occasionally, however, the branch in a particular country may offer a somewhat higher interest rate to compensate for a depositor's reluctance to buy deposits in that country because of greater political risk (Aliber, 1980). The overnight London interbank offer rate (LIBOR) would be a better measure to use because the LIBOR is a benchmark rate in the Euromarket as well as in other financial markets. However the British Bankers' Association did not publish the overnight LIBOR before January 2001.

weekends, US holidays and seven trading days when the overnight Eurodollar rates are not available from the data set, the total number of observations is 3279. Because the one-week reserve maintenance period ending on Wednesday changed to a two-week reserve accounting system in February 1984, there is a two-week maintenance period and an almost simultaneous reserve accounting system for the period covered in this study as shown in Fig. 1. Fed funds rates and overnight Eurodollar rates are plotted in Panel A and B of Fig. 2 respectively. Panel C of Fig. 2 plots the differential

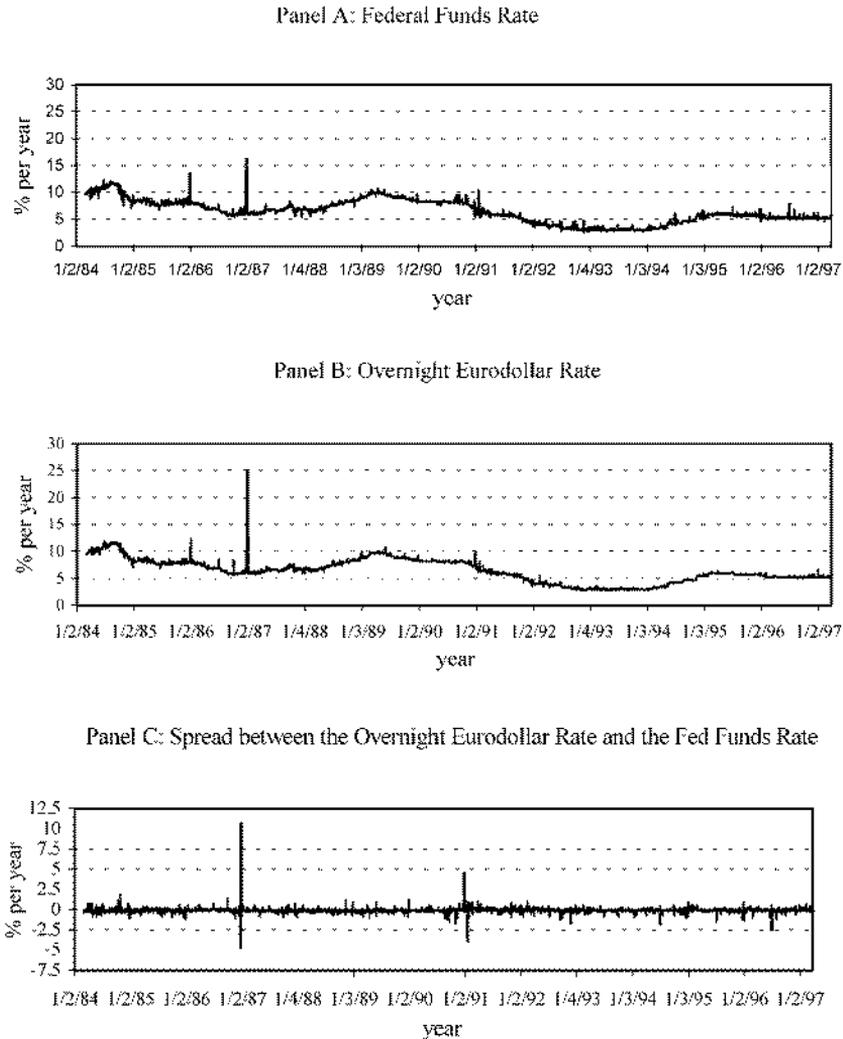


Fig. 2. The Fed funds rate, the overnight Eurodollar rate and the spread between the overnight Eurodollar rate and the Fed funds rate, 1984:03–1997:03. Panel A displays the daily effective Fed funds rate for the Fed funds rate. Panel B displays the daily overnight Eurodollar deposit rate in London for the overnight Eurodollar rate. Panel C displays the differential between two overnight rates.

Table 1

Summary statistics for the Fed funds rate, the overnight Eurodollar rate and their differential, 1984:03–1997:03

	i_t	Δi_t	r_t	Δr_t	sp_t
Mean	6.438	−0.001	6.355	−0.001	−0.083
Maximum	16.170	7.790	25.000	13.500	0.650
Minimum	2.580	−7.890	2.750	−17.120	−4.670
Standard deviation	2.148	0.383	2.140	0.450	0.332
	2.134**	0.311**	2.112**	0.206**	0.262**
Skewness	0.191	0.170	0.329	−8.188	9.566
	0.149**	0.688**	0.134**	−0.594**	0.240**
Kurtosis	2.557	127.366	4.082	896.240	363.290
	2.402**	18.842**	2.426**	28.070**	53.502**

The summary statistics are calculated from the daily effective Fed funds rate for the daily Fed funds rate and the overnight Eurodollar deposit rate for the daily overnight Eurodollar rate. The sample period is from March 1, 1984 to March 26, 1997. The Fed funds rate on date t is denoted i_t ; the change in the Fed funds rate on date t , $i_t - i_{t-1}$, is denoted Δi_t ; the overnight Eurodollar rate on date t is denoted r_t ; the change in the overnight Eurodollar rate, $r_t - r_{t-1}$, is denoted Δr_t ; the differential between the overnight Eurodollar rate and the effective Fed funds rate, $r_t - i_t$, is denoted sp_t . ** represents the standard deviation, skewness and kurtosis leaving out three observations, December 31, 1985 and December 30 and 31, 1986.

between the Fed funds rate and the overnight Eurodollar rate. The Fed funds rate and the overnight Eurodollar rate show very similar movements and change very little on most days. Table 1 provides summary statistics of the Fed funds rate, the Eurodollar rate and their differential. Changes in Fed funds rates and changes in overnight Eurodollar rates have the biggest outliers at the same calendar dates (the last days of 1985 and 1986) when the last day of the year fell on the end of a reserve maintenance period. On the last day of 1986, the Fed funds rate and the overnight Eurodollar rate changed about 800 basis points and 1700 basis points respectively. The next biggest changes in the Fed funds rate and the overnight Eurodollar rate were observed at the end of 1985: 438 basis points and 425 basis points respectively. The standard deviation of the change in the Fed funds rate is smaller than that of the change in the overnight Eurodollar rate as seen in Table 1. However, by leaving out three observations (December 31, 1985 and December 30 and 31, 1986), the standard deviation of the change in the Fed funds rate becomes larger than that of the change in the overnight Eurodollar rate. Larger outliers for the overnight Eurodollar rate make the standard deviation of the overnight Eurodollar rate the same as that of the Fed funds rate. The large kurtosis of the changes in Fed funds rates, changes in overnight Eurodollar rates and the differential between the two interest rates indicates fat-tail distributions, requiring the analysis to consider large outliers.

4. Model specification

Both overnight Eurodollars and Fed funds are US dollar denominated and traded in large amounts for one business day. Therefore, the Fed funds rate and the

overnight Eurodollar rate are comparable, and the differential between the two interest rates is not involved with the term structure of interest rates or the capital gain on foreign currency.² These two rates are related by the following identity:

$$r_t \equiv i_t + \text{sp}_t, \quad (1)$$

where r_t is the overnight Eurodollar rate, i_t is the Fed funds rate and sp_t is the differential or the spread between the overnight Eurodollar rate and the Fed funds rate on day t . The conditional expected values are

$$E(r_t|I_{t-1}) \equiv E(i_t|I_{t-1}) + E(\text{sp}_t|I_{t-1}), \quad (2)$$

where $E(\cdot|I_{t-1})$ is the conditional expectation operator with respect to the information set I_{t-1} , which is observed at date $t - 1$ in this bivariate model,

$$I_{t-1} = \{i_{t-1}, i_{t-2}, \dots, r_{t-1}, r_{t-2}, \dots, t\}. \quad (3)$$

Reserves held on any day of the two-week maintenance period are perfect substitutes for the purpose of meeting reserve requirements. The Fed funds rate would follow a martingale within a two-week maintenance period under the following conditions: banks are risk neutral; the reserve requirements are the only reason why banks hold reserves; and there is no friction to participate in the Fed funds market (Hamilton, 1996). Hamilton (1996) tested the martingale hypothesis during the sample period from March 1984 to November 1990, taking into account the day of a maintenance period, US holidays, the end of a quarter and the end of a year. The estimated results showed that the Fed funds rate did not follow a martingale and banks did not consider reserves held on different days of the maintenance period as perfect substitutes. The rate fell during the reserve maintenance period until the second Friday. It sharply decreased on Fridays and jumped back up on Mondays. It fell before holidays and rose after holidays. It surged upwards on settlement Wednesdays. The variances increase during the last three days of the maintenance period and are highest on settlement Wednesday. Spindt and Hoffmeister (1988) and Griffiths and Winters (1995) found similar results. Hamilton (1996) explained these tendencies as the result of line limits, transaction costs and reserve accounting conventions in the Fed funds market. First, the line limits caused the Fed funds rate to fall during the reserve maintenance period until the second Friday. A bank wanted to borrow early in the maintenance period to avoid a risk of running up against line limits even if it knew the Fed funds rate would be cheaper later on in the maintenance period. Second, the Fed funds rate tended to drop on Fridays and before holidays and increased on Mondays and after holidays. The banks wanted to supply weekend funds, in order to earn three days' worth of interest. Furthermore, since a bank did not want unneeded excess reserves and it was not sure whether it needed the full reserve credit it could obtain from a multiple day loan (such as a two-day

² The differential between the Fed funds rate and the overnight Eurodollar rate may signal changes in political risks. Because the two funds are traded overnight, the political risk would be very small.

loan, a three-day loan or a four-day loan), it preferred not to borrow such a loan. Third, the Fed funds rate tended to rise at the end of the maintenance period. Since a bank could perceive more information on needed reserves on settlement Wednesdays due to the reserve accounting system, it delayed its borrowing until then to avoid unneeded reserves. Another factor to deviate from the martingale hypothesis is that overnight overdraft penalties limit the willingness of banks to substitute reserve holdings across the days of the maintenance period. Hamilton (1996) also noted that the martingale hypothesis might not restrict the Wednesday–Thursday change across different maintenance periods. This is because reserves on the first Thursday of a maintenance period are not perfectly substitutable for reserves of the day before, even though there is a provision allowing banks to substitute some amount of reserves across maintenance periods.

I extend Hamilton’s (1996) model for the Fed funds rate and add lagged overnight Eurodollar rates to the explanatory variables. Many researchers found changes in interest rates on money market instruments as the last day of a quarter approached, which is called the turn-of-the-quarter effect. Popular explanations are window dressing (Allen and Saunders, 1992; Musto, 1997) and preferred habitat for liquidity (Ogden, 1987; Griffiths and Winters, 1997). Therefore, the Fed funds rate was also allowed to deviate from the martingale hypothesis on the last day of a quarter and the quarter-end effects on the Fed fund rate or the overnight Eurodollar rate are not interpreted as a calendar day effect created by Federal Reserve regulations. If day t is the first day of a maintenance period or the first day of a quarter, the conditional mean for the Fed funds rate is specified as follows:

$$E(i_t|I_{t-1}) = \alpha_1 i_{t-1} + \alpha_2 i_{t-2} + \dots + \alpha_p i_{t-p} + \delta_1 r_{t-1} + \delta_2 r_{t-2} + \dots + \delta_q r_{t-q} + \eta_1 + \sum_{j=1}^8 \beta_j h_{jt}. \tag{4}$$

For all other days, the conditional mean of the Fed funds rate ³ is written as

$$E(i_t|I_{t-1}) = i_{t-1} + \phi_1 r_{t-1} + \phi_2 r_{t-2} + \dots + \phi_r r_{t-r} + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt}, \tag{5}$$

³ Because there are limited substitution opportunities across maintenance periods, the coefficients of the lagged r_t in Eq. (5) might differ depending on whether the day is during the current maintenance period or the previous maintenance period. Therefore, the dummy variables for the day of a maintenance period could affect the coefficients of the lagged overnight Eurodollar rate in Eq. (5). If day t is not the first day of a maintenance period or the first day of a quarter, the alternative model for Eq. (5) is

$$E(i_t|I_{t-1}) = i_{t-1} + \phi_1 r_{t-1} + (\phi_{21} + \phi_{22} d_{2t}) r_{t-2} + (\phi_{31} + \phi_{32} (d_{2t} + d_{3t})) r_{t-3} + (\phi_{41} + \phi_{42} (d_{2t} + d_{3t} + d_{4t})) r_{t-4} + \dots + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt}. \tag{5'}$$

Eq. (5') is different from Eq. (5) in that it includes new variables, $d_{2t} r_{t-2}$, $(d_{2t} + d_{3t}) r_{t-3}$, $(d_{2t} + d_{3t} + d_{4t}) r_{t-4}$, ...

where d_{st} for $s = 2, 3, \dots, 10$ is a dummy variable that equals 1 if day t is the s th day of the reserve maintenance period. For example, $d_{2t} = 1$ if day t is the second day of a maintenance period, the first Friday, and $d_{2t} = 0$ otherwise. The variable d_{10t} takes the value 1 for the last day of a maintenance period, a settlement Wednesday, and equals 0 otherwise. The variable h_{jt} for $j = 1, 2, \dots, 8$ is also a dummy variable to denote US holidays and the last day of a quarter. The dummy variable h_{1t} is equal to 1 if day t precedes a one-day holiday and 0 otherwise. Similarly, h_{2t} is the holiday dummy variable, which is equal to one on a day preceding a three-day holiday and zero on other days. The dummy variables h_{5t} to h_{8t} denote the last day of a quarter. The definitions of d_{st} and h_{jt} are denoted in Table 2 and Table 3.⁴ Griffiths and Winters (1995) eliminate all settlement periods containing holidays and quarter ends. However, US holidays influence the way to calculate required reserves and to invest idle cash over the non-trading period the same as weekends. The last days of a quarter should be also included because some of the last days of a quarter coincided with the settlement Wednesday even though the heavy flow of funds is observed through the banking system ahead of the quarter end.

If the overnight Eurodollar rate is affected by the Fed funds rate, the overnight Eurodollar rate might be predictable on the basis of lagged Fed funds rates, lagged overnight Eurodollar rates and calendar days. The conditional mean of the overnight Eurodollar rate is estimated by two separate equations because the conditional mean of the Fed funds rate has different specifications depending on which day of a two-week reserve maintenance period day t corresponds to and whether day t is the first day of a quarter. On the first day of a maintenance period or the first day of a quarter, the following bivariate model gives the conditional mean of the overnight Eurodollar rate:

$$E(r_t | I_{t-1}) = a_1 i_{t-1} + a_2 i_{t-2} + \dots + a_r i_{t-r} + b_1 r_{t-1} + b_2 r_{t-2} + \dots + b_s r_{t-s} + \dot{\eta}_1 + \sum_{j=1}^8 \dot{\beta}_j h_{jt}. \quad (6)$$

On other days, it is specified as

$$E(r_t | I_{t-1}) = c_1 i_{t-1} + c_2 i_{t-2} + \dots + c_u i_{t-u} + k_1 r_{t-1} + k_2 r_{t-2} + \dots + k_w r_{t-w} + \sum_{s=2}^{10} \dot{\eta}_s d_{st} + \sum_{j=1}^8 \dot{\beta}_j h_{jt}. \quad (7)$$

The definitions of dummy variables, d_{st} and h_{jt} , are the same as those given in Eqs. (4) and (5).

⁴ In December 1990, the Fed cut the reserve requirement on net Eurocurrency liabilities from 3% to 0%. To see the possible different use of the Eurodollar market by US banks, h_{jt} included the dummy variable equal to 1 if day t is before January 1991 and 0 otherwise. However, the dummy variable is statistically insignificant so it is not included in estimation equations in this paper. The 3% reserve requirement on net borrowing (borrowing minus placements) of Euros might not change a bank's choice of money markets.

The spread sp_t is treated as the residual variable in identity (1). Once the determinants of i_t and r_t are specified, the conditional expectation for sp_t is redundant and does not contain any additional information. The conditional mean of the spread can be calculated by Eqs. (2) and (4)–(7). If there is no friction between or in the two markets and funds in the two markets are perfectly substitutable, the spread would not be predictable.

Because Spindt and Hoffmeister (1988), Griffiths and Winters (1995) and Hamilton (1996) showed that the Fed funds rate exhibited heteroskedasticity, the error terms of Eqs. (4)–(7) are allowed to be heteroskedastic:

$$y_t = E(y_t|I_{t-1}) + \sigma_t v_t, \quad (8)$$

where y_t denotes the dependent variable, the Fed funds rate or the overnight Eurodollar rate and σ_t^2 is a function of date t , lagged Fed funds rates and lagged overnight Eurodollar rates. The innovation v_t is a zero-mean, i.i.d. random variable. To capture the frequent small changes and infrequent large changes, which imply high kurtosis, it is assumed that v_t has a mixture of Normal distributions given by (9) as Hamilton (1996) suggested. The innovation v_t is drawn from a $N(0, 1)$ distribution with a probability p and from a $N(0, \tau^2)$ distribution, which has a different variance, with a probability $(1 - p)$. The density of a mixture of two Normal distributions is

$$g(v_t; \theta) = \frac{p}{\sqrt{2\pi}} \exp\left(\frac{-v_t^2}{2}\right) + \frac{1-p}{\tau\sqrt{2\pi}} \exp\left(\frac{-v_t^2}{2\tau^2}\right), \quad (9)$$

where θ is a vector of population parameters that includes p and τ^2 . The conditional variance of this distribution is given by

$$E\{[y_t - E(y_t|I_{t-1})]^2|I_{t-1}\} = \sigma_t^2[p + (1-p)\tau^2]. \quad (10)$$

I followed Hamilton's (1996) modification of Nelson's (1991) exponential GARCH (EGARCH) model for the log of the conditional variance of y_t . It is assumed that GARCH effects are integrated and ζ_s has the same value for day 2 to day 7 in Eq. (12):

$$\zeta_2 = \zeta_3 = \dots = \zeta_7. \quad (11)$$

I also accept the hypothesis that the most important determinants of the conditional variance are the deviation of the log of the conditional variance from its unconditional expectation on the previous day and the average difference between the log of the conditional variance and its unconditional expectation during the previous two-week maintenance period (Hamilton, 1996). Hence the log of the conditional variance is

$$\begin{aligned} \ln(\sigma_t^2) - \sum_{s=1}^{10} \xi_s d_{st} - \sum_{j=1}^8 \kappa_j h_{jt} &= \delta \left[\ln(\sigma_{t-1}^2) - \sum_{s=1}^{10} \xi_s d_{st-1} - \sum_{j=1}^8 \kappa_j h_{jt-1} \right] \\ &+ (1 - \delta) \frac{1}{10} \sum_{m=b_t}^{l_t} \left[\ln(\sigma_m^2) - \sum_{s=1}^{10} \xi_s d_{sm} - \sum_{j=1}^8 \kappa_j h_{jm} \right] \\ &+ \alpha[q(v_{t-1}) - Eq(v_{t-1}) + \lambda v_{t-1}], \end{aligned} \tag{12}$$

where b_t and l_t are the beginning and the ending days of the previous maintenance period respectively. A positive value of $\alpha\lambda$ indicates that volatility in the conditional variance tends to rise when innovations of y_{t-1} are positive. Because the non-differentiability of the likelihood function complicates numerical maximization of the likelihood at $v_{t-1} = 0$, $q(v_{t-1})$ takes the following form:

$$q(v_{t-1}) = \begin{cases} (1 + v_{t-1}^2)/2 & \text{for } |v_{t-1}| < 1, \\ |v_{t-1}| & \text{for } |v_{t-1}| \geq 1. \end{cases} \tag{13}$$

This function is differentiable everywhere including $v_{t-1} = 0$. The expected value of $q(v_{t-1})$ is calculated by numerically integrating $q(v_{t-1})$ with the density of Eq. (9) with respect to v_{t-1} .

Since

$$y_t = E(y_t|I_{t-1}) + \sigma_t v_t = \phi(v_t), \tag{14}$$

the conditional density of y_t would be

$$f(y_t|I_{t-1}) = g(v_t) \left| \frac{dv_t}{dy_t} \right|, \tag{15}$$

where

$$v_t = \phi^{-1}(y_t) = [y_t - E(y_t|I_{t-1})]/\sigma_t. \tag{16}$$

$E(y_t|I_{t-1})$ is specified in Eqs. (4)–(7). Hence the log of the density is

$$\ln f(y_t|I_{t-1}) = \ln[g(v_t)] - \ln(\sigma_t^2)/2. \tag{17}$$

Maximum likelihood estimates are calculated by maximizing the conditional log likelihood with respect to the population parameters subject to two constraints, $0 \leq \rho \leq 1$ and $\tau^2 > 0$.

5. Empirical results

The maximum likelihood estimates⁵ for the Fed funds rate and the overnight Eurodollar rate are reported in Tables 2–6. If day t is the first day of a maintenance

⁵ The Akaike information criterion (AIC) and the Bayesian Schwarz information criterion (BIC) are used to determine the lag length for the conditional means of the Fed funds rate, the overnight Eurodollar rate and their spread. The two information criteria gave consistent results. The estimated Eqs. (18)–(23) are superior under the two criteria.

Table 2
Maximum likelihood estimates of the conditional mean (day of the reserve maintenance period effects)

<i>s</i>	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$	$E(sp_t I_{t-1})$
	η_s	$\hat{\eta}_s$	$\Delta\eta_s$
1 (first Thursday)	0.003 (0.012)	-0.017 (0.016)	-0.037* (0.017)
2 (first Friday)	-0.059* (0.005)	-0.032* (0.006)	0.009 (0.008)
3 (first Monday)	0.058* (0.005)	0.028* (0.005)	-0.057* (0.007)
4 (first Tuesday)	-0.053* (0.004)	-0.012* (0.005)	0.030* (0.007)
5 (first Wednesday)	-0.034* (0.004)	-0.011* (0.005)	0.007 (0.006)
6 (second Thursday)	0.011* (0.004)	-0.017* (0.005)	-0.043* (0.006)
7 (second Friday)	-0.043* (0.004)	-0.023* (0.005)	0.009 (0.008)
8 (second Monday)	0.080* (0.006)	0.045* (0.006)	-0.049* (0.008)
9 (second Tuesday)	-0.060* (0.007)	0.004 (0.006)	0.050* (0.008)
10 (second Wednesday)	0.136* (0.017)	0.052* (0.007)	-0.107* (0.019)

The letter *s* indicates which day of a two-week reserve maintenance period day *t* falls on. For example, *s* is equal to 1 if day *t* is the first Thursday of a maintenance period and *s* is equal to 10 if day *t* is the last day of a maintenance period, which is settlement Wednesday. The values, η_s , $\hat{\eta}_s$ and $\Delta\eta_s$, of the first, second and third columns indicate the effect of the dummy variable for day *s* of the reserve maintenance period on the conditional mean of the Fed funds rate, the overnight Eurodollar rate and the differential between the Fed funds rate and the overnight Eurodollar rate respectively. Standard errors are in parentheses. * denotes statistical significance at the 5% level.

period or the first day of a quarter, then the conditional mean of the Fed funds rate is as follows:

$$\begin{aligned}
 E(i_t|I_{t-1}) = & 0.162i_{t-1} + 0.027i_{t-2} + 0.078i_{t-3} + 0.225i_{t-4} + 0.206i_{t-5} \\
 & \quad (0.018) \quad (0.052) \quad (0.035) \quad (0.046) \quad (0.055) \\
 & - 0.015r_{t-1} + 0.289r_{t-2} + 0.057r_{t-3} - 0.177r_{t-4} + 0.156r_{t-5} \\
 & \quad (0.022) \quad (0.057) \quad (0.043) \quad (0.037) \quad (0.049) \\
 & + \eta_1 + \sum_{j=1}^8 \beta_j h_{jt}, \tag{18}
 \end{aligned}$$

where the numbers in parentheses are the standard errors. For other typical days, the conditional mean is estimated as

$$E(i_t|I_{t-1}) = i_{t-1} + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt}. \tag{19}$$

Table 3

Maximum likelihood estimates of the conditional mean (US holiday and the last day of a quarter effects)

<i>j</i>	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$	$E(sp_t I_{t-1})$
	β_j	$\hat{\beta}_j$	$\Delta\beta_j$
1	-0.029 (0.028)	-0.003 (0.015)	0.026 (0.025)
2	-0.022* (0.008)	-0.008 (0.008)	0.015 (0.011)
3	0.079* (0.020)	-0.021 (0.014)	-0.097* (0.020)
4	0.198* (0.012)	0.069* (0.009)	-0.161* (0.012)
5	0.367* (0.081)	0.242* (0.054)	-0.120 (0.095)
6	-0.478* (0.184)	-0.052 (0.112)	0.048 (0.273)
7	0.033 (0.018)	-0.011 (0.012)	-0.029 (0.027)
8	-0.020 (0.052)	0.027 (0.031)	0.037 (0.020)

The letter *j* indicates US holidays and the last day of a quarter, *j* = 1 indicates that day *t* precedes a one-day holiday; *j* = 2 indicates that day *t* precedes a three-day holiday; *j* = 3 indicates that day *t* follows a one-day holiday; *j* = 4 indicates that day *t* follows a three-day holiday; *j* = 5 indicates that day *t* is the last day of the first, second, third or fourth quarter; *j* = 6 indicates that day *t* is the last day of the year; *j* = 7 indicates that day *t* is one day before, on or one day after the last day of the first, second, third or fourth quarter; *j* = 8 indicates that day *t* is two days before, one day before, on, one day after or two days after the end of the year. The values, β_j , $\hat{\beta}_j$ and $\Delta\beta_j$, of the first, second and third columns indicate the effects of the dummy variable h_{jt} on the conditional mean of the Fed funds rate, the overnight Eurodollar rate and the differential between the Fed funds rate and the overnight Eurodollar rate respectively. Standard errors are in parentheses. * denotes statistical significance at the 5% level.

The hypothesis, $H_0 : \phi_1 = \phi_2 = \dots = \phi_r = 0$ in Eq. (5), is not rejected and none of the lagged overnight Eurodollar rates are significant in Eq. (19).⁶ The lagged overnight Eurodollar rates can help predict the Fed funds rate only for the first day of a

⁶ The estimated conditional mean for Eq. (4) and (5') are Eqs. (18') and (19') respectively.

$$E(i_t|I_{t-1}) = \underset{(0.015)}{0.163}i_{t-1} + \underset{(0.028)}{0.023}i_{t-2} + \underset{(0.029)}{0.086}i_{t-3} + \underset{(0.043)}{0.236}i_{t-4} + \underset{(0.054)}{0.109}i_{t-5} - \underset{(0.033)}{0.017}r_{t-1} + \underset{(0.055)}{0.282}r_{t-2} + \underset{(0.045)}{0.060}r_{t-3} - \underset{(0.036)}{0.173}r_{t-4} + \underset{(0.052)}{0.1161}r_{t-5} + \eta_1 + \sum_{j=1}^8 \beta_j h_{jt}, \tag{18'}$$

$$E(i_t|I_{t-1}) = i_{t-1} - \underset{(0.015)}{0.037}r_{t-1} + \underset{(0.017)}{(-0.019 + 0.017d_{2t})}r_{t-2} + \underset{(0.003)}{(0.037 - 0.017(d_{2t} + d_{3t}))}r_{t-3} + \underset{(0.013)}{(0.017 + 0.009(d_{2t} + d_{3t} + d_{4t}))}r_{t-4} + \sum_{s=2}^{10} \eta_s d_{st} + \sum_{j=1}^8 \beta_j h_{jt}. \tag{19'}$$

The estimated parameters ϕ_1 , ϕ_{22} , ϕ_{31} , ϕ_{32} , and ϕ_{42} are significant but the values of the coefficients are very small. The estimated values of η_s and β_j (which my paper is interested in) for Eqs. (18) and (19) are very similar to those for Eqs. (18') and (19'). The estimated Eqs. (18') and (19') have bigger values for the two information criteria, AIC and BIC, than Eqs. (18) and (19). Therefore, Eqs. (18) and (19) are chosen as the conditional mean of the Fed funds rate.

Table 4
Maximum likelihood estimates of the conditional variance (day of the reserve maintenance period effects)

<i>s</i>	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$
	ξ_s	$\dot{\xi}_s$
1 (first Thursday)	−3.959* (0.487)	−3.487* (0.534)
2 (first Friday)	−3.962* (0.477)	−4.409* (0.545)
3 (first Monday)	{−3.962}	{−4.409}
4 (first Tuesday)	{−3.962}	{−4.409}
5 (first Wednesday)	{−3.962}	{−4.409}
6 (second Thursday)	{−3.962}	{−4.409}
7 (second Friday)	{−3.962}	{−4.409}
8 (second Monday)	−3.219* (0.482)	−3.985* (0.558)
9 (second Tuesday)	−2.929* (0.490)	−3.956* (0.543)
10 (second Wednesday)	−1.286* (0.491)	−3.225* (0.551)

The letter *s* indicates which day of a two-week reserve maintenance period day *t* falls on. For example, *s* is equal to 1 if day *t* is the first Thursday of a maintenance period and *s* is equal to 10 if day *t* is the last day of a maintenance period, which is settlement Wednesday. The values, ξ_s and $\dot{\xi}_s$, indicate the effect of the dummy variable for day *s* of the reserve maintenance period on the natural log of σ_t^2 of the Fed funds rate and the overnight Eurodollar rate respectively. Standard errors are in parentheses. * denotes statistical significance at the 5% level. {·} indicates the restricted value.

maintenance period or the first day of a quarter. The value η_s for $s = 2, 3, \dots, 10$ can be interpreted as the average change in the Fed funds rate between day *s* and *s* − 1. For example, η_2 governs the average change in the Fed funds rate between the first Thursday and first Friday. The maximum likelihood estimates of η_s and β_j are reported in the first column of Tables 2 and 3 respectively. The main patterns in Griffiths and Winters (1995) and Hamilton (1996) are reproduced in this study. The Fed funds rate tends to decrease until the second Friday of a maintenance period. The Fed funds rate has a tendency to fall on Fridays (η_2 and η_7), Tuesdays (η_4 and η_9), first Wednesdays (η_5) and the day before a three-day holiday (β_2), and to rise on Mondays (η_3 and η_8) and the day after a one-day or a three-day holiday (β_3 and β_4). It rapidly rises on settlement Wednesday (η_{10}).

For the first day of a reserve maintenance period or the first day of a quarter, the expected overnight Eurodollar rate is described by

$$\begin{aligned}
 E(r_t|I_{t-1}) = & 0.072i_{t-1} + 0.138i_{t-2} + 0.087i_{t-3} + 0.066r_{t-1} + 0.364r_{t-2} \\
 & (0.012) \quad (0.038) \quad (0.034) \quad (0.033) \quad (0.077) \\
 & + 0.268r_{t-3} + \hat{\eta}_1 + \sum_{j=1}^8 \hat{\beta}_j h_{jt}. \tag{20} \\
 & (0.052)
 \end{aligned}$$

Table 5
Maximum likelihood estimates of the conditional variance (holiday and the last day of a quarter effects)

<i>j</i>	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$
	κ_j	$\dot{\kappa}_j$
1	{0.000}	{0.000}
2	{0.000}	{0.000}
3	{0.000}	{0.000}
4	{0.000}	{0.000}
5	2.116* (0.271)	2.658* (0.331)
6	-0.828 (0.631)	-0.655 (0.725)
7	1.295* (0.198)	0.332 (0.223)
8	2.443* (0.262)	2.148* (0.344)

The letter *j* indicates US holidays and the last day of a quarter. *j* = 1 indicates that day *t* precedes a one-day holiday; *j* = 2 indicates that day *t* precedes a three-day holiday; *j* = 3 indicates that day *t* follows a one-day holiday; *j* = 4 indicates that day *t* follows a three-day holiday; *j* = 5 indicates that day *t* is the last day of the first, second, third or fourth quarter; *j* = 6 indicates that day *t* is the last day of the year; *j* = 7 indicates that day *t* is one day before, on or one day after the last day of the first, second, third or fourth quarter; *j* = 8 indicates that day *t* is two days before, one day before, on, one day after or two days after the end of the year. The values, κ_j and $\dot{\kappa}_j$, of the first and second columns indicate the effects of the dummy variable h_{jt} on the natural log of σ_t^2 of the Fed funds rate and the overnight Eurodollar rate respectively. Standard errors are in parenthesis. * denotes statistical significance at the 5% level. {·} indicates the restricted value.

For other days, it is

$$\begin{aligned}
 E(r_t|I_{t-1}) = & \underset{(0.015)}{0.399}i_{t-1} - \underset{(0.009)}{0.038}i_{t-2} - \underset{(0.007)}{0.026}i_{t-3} + \underset{(0.017)}{0.606}r_{t-1} + \underset{(0.009)}{0.055}r_{t-3} \\
 & + \sum_{s=2}^{10} \dot{\eta}_s d_{st} + \sum_{j=1}^8 \dot{\beta}_j h_{jt}. \tag{21}
 \end{aligned}$$

The lagged Fed funds rates can help predict the overnight Eurodollar rate on any day of a maintenance period. In part, it could be because yesterday's Fed funds rate was quoted in the US after yesterday's Eurodollar rate was reported in London, so yesterday's Fed funds rate has more recent information than yesterday's Eurodollar rate. The effect of lagged Fed funds rates on the overnight Eurodollar rate is larger for days other than the first day of a new period. In contrast, the lagged overnight Eurodollar rates help predict the Fed funds rate only on the first day of a new period. This result might show that the Fed funds rate influences the overnight Eurodollar rate more on days other than the first day of a new period. The second column of Tables 2 and 3 indicates the values for dummy variables, $\dot{\eta}_s$ and $\dot{\beta}_j$ of Eqs. (20) and (21) for $s = 1, 2, \dots, 10$, and $j = 1, 2, \dots, 8$. The estimated coefficients of the calendar day dummies for the conditional mean of the overnight Eurodollar rate have the same signs as those of the Fed funds rate, except the second Thursday $\dot{\eta}_6$. The three coefficients, $\dot{\eta}_9$, $\dot{\beta}_2$ and $\dot{\beta}_3$, do not show calendar day effect whereas those of

Table 6
Maximum likelihood estimates of other parameters

Parameters	$E(i_t I_{t-1})$	$E(r_t I_{t-1})$
δ	0.472* (0.043)	0.595* (0.061)
α	0.472* (0.029)	0.339* (0.031)
\aleph	0.191* (0.043)	0.128* (0.045)
p	0.829* (0.014)	0.831* (0.016)
τ^2	9.888* (0.741)	11.703* (0.856)

For each of the parameters listed, the maximum likelihood estimates maximize the following log likelihood for $T = 3279$,

$$L = \sum_{t=2}^T \ln f(v_t|I_{t-1}) = \sum_{t=2}^T (\ln [g(v_t)] - \ln(\sigma_t^2)/2),$$

where

$$y_t = E(y_t|I_{t-1}) + \sigma_t v_t,$$

$$g(v_t; \theta) = \frac{p}{\sqrt{2\pi}} \exp\left(-\frac{v_t^2}{2}\right) + \frac{1-p}{\tau\sqrt{2\pi}} \exp\left(-\frac{v_t^2}{2\tau^2}\right),$$

$$\begin{aligned} \ln(\sigma_t^2) &= \sum_{s=1}^{10} \xi_s d_{st} - \sum_{j=1}^8 \kappa_j h_{jt} \\ &= \delta \left[\ln(\sigma_{t-1}^2) - \sum_{s=1}^{10} \xi_s d_{st-1} - \sum_{j=1}^8 \kappa_j h_{jt-1} \right] \\ &\quad + (1-\delta) \frac{1}{10} \sum_{m=b_t}^{l_t} \left[\ln(\sigma_m^2) - \sum_{s=1}^{10} \xi_s d_{sm} - \sum_{j=1}^8 \kappa_j h_{jm} \right] + \alpha [q(v_{t-1}) - Eq(v_{t-1}) + \aleph v_{t-1}], \end{aligned}$$

and y_t denotes the dependent variable, the Fed funds rate or the overnight Eurodollar rate, σ_t^2 is the conditional variance; d_{st} (d_{sm}) and h_{jt} (h_{jm}) are dummy variables to indicate the day of a maintenance period, and US holidays and the last day of a quarter respectively. The innovation v_t has a mixture of Normal distributions, drawn from a $N(0, 1)$ distribution with probability p and from a $N(0, \tau^2)$ distribution, which has a different variance, with a probability $(1 - p)$. * denotes statistical significance at the 5% level.

the Fed funds rate do. The second Thursday gives a negative effect on the conditional mean of the overnight Eurodollar rate while it gives a positive effect on the conditional mean of the Fed funds rate. The negative effect of the second Thursday is consistent with the tendency of the Fed funds rate to fall during the reserve maintenance period until the second Friday. Thus, the parameter of the second Thursday can be considered the result of the US reserve accounting system. The absolute values of the coefficients of the overnight Eurodollar rate are generally slightly smaller with the same signs. However, some of them ($\hat{\eta}_{10}$ and $\hat{\beta}_4$) are quite different in magnitude from those of the Fed funds rate (η_{10} and β_4).

To test the hypotheses, $H_0: \eta_s = \hat{\eta}_s$ and $\beta_j = \hat{\beta}_j$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, 3, 4$. I test $H_0: \Delta\eta_s = 0$ and $\Delta\beta_j = 0$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, 3, 4$ in

the following Eqs. (22) and (23).⁷ On the first day of a maintenance period or the first day of a quarter, the estimated conditional mean of the spread is as follows:

$$E(\text{sp}_t | I_{t-1}) = \underbrace{-0.045}_{(0.017)} i_{t-1} + \underbrace{0.149}_{(0.022)} r_{t-1} - \underbrace{0.117}_{(0.021)} r_{t-2} + \Delta \hat{\eta}_1 + \sum_{j=1}^8 \Delta \hat{\beta}_j h_{jt}. \quad (22)$$

On other typical days, it is

$$E(\text{sp}_t | I_{t-1}) = \underbrace{-0.478}_{(0.019)} i_{t-1} + \underbrace{0.475}_{(0.019)} r_{t-1} + \sum_{s=2}^{10} \Delta \hat{\eta}_s d_{st} + \sum_{j=1}^8 \Delta \hat{\beta}_j h_{jt}, \quad (23)$$

where $\text{sp}_t = r_t - i_t$, $\Delta \eta_s = \dot{\eta}_s - \eta_s$ and $\Delta \beta_j = \dot{\beta}_j - \beta_j$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$. If $\Delta \eta_s = 0$ and $\Delta \beta_j = 0$, the difference between two overnight interest rates is not predictable based on calendar days. The maximum likelihood estimates of the values for $\Delta \hat{\eta}_s$ and $\Delta \hat{\beta}_j$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, \dots, 8$ are reported in the third column of Tables 2 and 3. Since the coefficients of i_{t-1} and r_{t-1} are almost the same in Eq. (23),⁸ an AR(1) process can describe the conditional mean of the spread on a typical day:

$$E(\text{sp}_t | I_{t-1}) = \underbrace{0.488}_{(0.019)} \text{sp}_{t-1} + \sum_{s=2}^{10} \Delta \hat{\eta}_s d_{st} + \sum_{j=1}^8 \Delta \hat{\beta}_j h_{jt}. \quad (24)$$

The value of the AR(1) coefficient is positive, meaning a positive correlation between sp_t and sp_{t+1} . If the difference between the overnight Eurodollar rate and the effective Fed funds rate is negative today, the difference is expected to be reduced but still negative tomorrow. The spread is predictable on the basis of yesterday's spread and dummy variables. Several papers have included lagged stock excess returns to estimate a stock excess return since discontinuous trading in the stocks makes up the index (Scholes and Williams, 1997; Lo and MacKinlay, 1988; Nelson, 1991). The Scholes and Williams (1997) model proposed an MA(1) process for index returns, while the Lo and MacKinlay (1988) and Nelson (1991) models suggested an AR(1) process. Canova and Marrinan (1995) empirically found that there is some weak positive serial correlation in excess returns between several financial markets but they failed to account for the serial correlation.

⁷ Since the spread is treated as the residual, its conditional mean can be calculated by Eqs. (18)–(21). If day t is the first day of a maintenance period or the first day of a quarter, then the conditional mean of the spread is calculated by subtracting (18) from (20). On a typical day, it is calculated by subtracting (19) from (21). To check which dummy variables are significant, the conditional mean of the spread is estimated by maximum likelihood in Eqs. (22) and (23). There are some discrepancies between the values of calculated coefficients and the estimated ones in (22) and (23) because Eqs. (18)–(23) are estimated by maximum likelihood.

⁸ The likelihood ratio test rejects the null hypothesis that the coefficient of $r_t(z_1)$ and the negative value of the coefficient of $i_t(-z_2)$ of Eq. (23) are the same ($z_1 = -z_2$) because the standard errors of the two coefficients are very small. However the likelihood ratio test does not reject the null hypothesis of $z_1 + 0.003 = -z_2$. Therefore, the relationship of z_1 and z_2 is considered to be $z_1 = -z_2$.

Eqs. (22) and (23) are used to test whether calendar day effects are equal for the conditional mean of the overnight Eurodollar rate and the Fed funds rate. The predicted value $\Delta\hat{\eta}_s = 0$ and $\Delta\hat{\beta}_j = 0$, if and only if $\hat{\eta}_s = \eta_s$ and $\hat{\beta}_j = \beta_j$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, 3, 4$. Remember that $\Delta\eta_s = \hat{\eta}_s - \eta_s$ and $\Delta\beta_j = \hat{\beta}_j - \beta_j$. The null hypothesis $H_0: \Delta\eta_s = 0$ or $\Delta\beta_j = 0$ for $s = 1, 2, \dots, 10$ and $j = 1, 2, 3, 4$ is strongly rejected. The significant coefficients of $\Delta\eta_s$ and $\Delta\beta_j$ imply that the calendar day effect on the conditional mean is different between the Fed funds rate and the overnight Eurodollar rate. As the third column of Tables 3 and 4 shows, the magnitudes of the calendar day effects on the conditional mean of the overnight Eurodollar rate are less than, or equal to those on the Fed funds rate.⁹ The average positive effect of settlement Wednesday on the overnight Eurodollar rate is smaller than that on the Fed funds rate. The downward pressure on the Fed funds rate does not appear on the overnight Eurodollar rate on the second Tuesday. This result is the same as Griffiths and Winters (1997) who found that government repos, which could be substitutes for Fed funds, did not show a significant decline on the second Tuesday but showed a significant increase on settlement Wednesday. The magnitude of the negative effect of Fridays is the same on the Fed funds rate and on the overnight Eurodollar rate but the positive effect of Mondays is bigger on the Fed funds rate. A negative weekend effect has been documented in US stock prices (Fama, 1965; French, 1980; Gibbons and Hess, 1981; Harris, 1986; Lakonishok and Maberly, 1990), in Treasury returns (Flannery and Protopapadakis, 1988) and in overnight repo rates (Griffiths and Winters, 1997). Griffiths and Winters (1997) suggest that the Friday and Monday effects on overnight repo rates are created not only by the Federal Reserve regulation of the settlement process but also by incentives of other participants in the repo market to avoid idle cash over non-trading weekends. In contrast, Kamath et al. (1995) do not find a negative weekend effect for the Eurodollar, the Euro Canadian dollar, the Euro Pound Sterling and the Euro Swiss Franc deposit rates. If a Tuesday follows a three-day holiday, the Fed funds rate and the overnight Eurodollar rate increase as on Mondays. The Friday and Monday effect and the US holiday effect on the Fed funds rate and on the overnight Eurodollar rate are interpreted as a result of Federal Reserve regulation, i.e. the incentive for US banks to avoid keeping unwanted excess reserves.

Tables 4 and 5 describe maximum likelihood estimates of the effects of calendar day dummies on the natural log of σ_t^2 in the Fed funds rate and in the overnight Eurodollar rate. Note that $\hat{\xi}_s$ and $\hat{\kappa}_j$ correspond to ξ_s and κ_j in (12) for the maximum likelihood estimates of the overnight Eurodollar rate. The variances of the Fed funds rate and the overnight Eurodollar rate are higher on the first day of a maintenance period than on other days ($\hat{\xi}_1 > \hat{\xi}_i$ and $\hat{\xi}_1 > \hat{\xi}_i$ for $i = 2, 3, \dots, 7$) and increase during the last three days of the maintenance period ($\hat{\xi}_i > \hat{\xi}_{i-1}$ and $\hat{\xi}_i > \hat{\xi}_{i-1}$ for $i = 8, 9, 10$). The variance tends to be larger on settlement Wednesdays than other days in both markets with less magnitude in the overnight Eurodollar rate. The conditional variance does not change around holidays in both markets.

⁹ Even if $\Delta\hat{\eta}_1$ is significant, neither η_1 nor $\hat{\eta}_1$ is significant so they are not discussed.

Maximum likelihood estimates for other parameters are presented in Table 6. The innovation v_t is assumed to be drawn from a mixture of two Normal distributions. About 83% of the Fed funds rate and the overnight Eurodollar rate are drawn from distribution 1, a Normal distribution with variance 1. With the probability of 0.17, v_t of the Fed funds rate comes from $N(0, 9.89)$. With the same probability, v_t of the overnight Eurodollar rate is drawn from $N(0, 11.7)$. They come from very similar distributions.

The overnight Eurodollar rate shows the same calendar day effects as the Fed funds rate with slightly smaller absolute magnitudes. The UK has a zero reserve requirement and UK banks must balance their position every day so the UK reserve settlement system does not result in these empirical regularities. These empirical results give support to the theory that the calendar day effects on the overnight Eurodollar rate are caused by the characteristics in the Fed funds market. Because this paper analyzes the overnight Eurodollar rate between 7:00 and 8:00 a.m. EST which is observed earlier than the Fed funds rate in the US, the calendar day effects on the overnight Eurodollar rate may be smaller than those on the Fed funds rate even though the overnight Eurodollar rate has the same calendar day effect as the Fed funds rate if the two rates are rated at the same time. Griffiths and Winters (1995) show that the morning Fed funds rate tends to fall only in the first week of a maintenance period which is different from the afternoon Fed funds rate tendencies, using high and low bid rates. The empirical results in this paper do not rule out the possibility that the overnight Eurodollar rate and the Fed funds rate observed at the same time show the same calendar day effect and that their difference is not predictable on the basis of calendar days.

The main upward and downward tendencies of the Fed funds rate and the overnight Eurodollar rate are always the same in both overnight markets by arbitrage activities. The predictability of the differential between the overnight Eurodollar rate and the Fed funds rate could provide an arbitrage opportunity between Fed funds and overnight Eurodollars. For example, on the first Monday of a maintenance period after a three-day holiday a top US bank could make a small arbitrage profit, on average, by purchasing Eurodollars of \$50 MM and selling them in the Fed funds market at the effective Fed funds rate. If the lending rate was the same as the deposit rate and yesterday's overnight Eurodollar rate was 8.3 basis points lower (the same as the average differential between the overnight Eurodollar rate and the Fed funds rate in Table 1), the profit of the bank is on average \$358¹⁰ before the phone bill and the brokerage fee are paid.¹¹ Reserve requirements are another cost of funds to the purchas-

¹⁰ On the first Monday of a maintenance period after a three-day holiday, the conditional mean of the differential between the overnight Eurodollar rate and the Fed funds rate is as follows:

$$E(e_{t|I_{t-1}}) = 0.48 \times -0.083 - 0.057 - 0.161 \approx -0.258.$$

The arbitrage profit on average would be

$$(0.258 \times 0.01) \times \$50,000,000 \times \left(\frac{1}{360}\right) \approx \$358.$$

¹¹ The brokerage fee is equal to \$0.50 per \$1 MM per day in the Fed funds market. It is also paid in the overnight Eurodollar market. Both the buyer and the seller pay the fee.

ing bank to raise funds in the Eurodollar market. US banks had to hold required reserves equal to 3% of net borrowings from the Euromarket until 1990. But the dummy variable for the period before 1990 is not significant as noted in Footnote 3.

Even though there is the opportunity for arbitrage profits, there are three major reasons why US banks are not actively out to make arbitrage profits. First, the primary job of a bank's Fed funds desk is that the bank holds no more excess reserves than the amount it can carry into the next settlement period and that the average rate it pays is lower than the effective Fed funds rate. Arbitrage transactions increase total profits but their low profitability often reduces the capital–asset ratio and the bank's average rate of return on assets, the critical financial ratios that measure capital adequacy and profitability. The Fed funds desk is looking for the cheapest available source of funds. At most major banks, the Fed funds desk is managed conservatively and they do not try to make money by dealing aggressively in funds (Stigum, 1990). Evidence of conservative management is that excess reserves are consistently positive. Second, the funds in the two markets have limited substitutability due to market frictions caused by the heterogeneity of banks. One factor on which banks are heterogeneous is creditworthiness. Different banks borrow funds at different rates depending on their creditworthiness of the borrower, general market conditions, and other factors.¹² A US bank does not always borrow Fed funds at the effective Fed funds rate because the effective Fed funds rate is a weighted average of the funds rates. Another factor for heterogeneity is line limits. The banks in the Fed funds market and the Eurodollar market sell funds only to banks to which they have established lines of credit and only up to the amount of the lines provided at the Fed funds market and the Eurodollar market. Thus even if a bank expects a lower overnight Eurodollar rate than the effective Fed funds rate, a bank that is normally a net buyer of Fed funds may have difficulty lending the Fed funds because it has an insufficient line to sell them. To develop correspondent banks that will sell funds to large banks, the large banks have to buy at the arranged rate whatever sums these banks offer even though they do not need to buy these funds. A bank may have to pay higher rates than the market rate because while funds are still offered in the market, they are not offered by banks with lines open to it. By the same token a bank posting non-competitive rates may still pick up deposits either because the lender has a line to only a few banks or because his lines to other banks are full. Third, the bid-asked spread prohibits the Fed funds desk from taking the arbitrage profit. Generally either 1/16 or 1/8 of a percentage point, equivalent to 6 or 12.5 basis points, separates the bid from the offer. The bid-asked spread is very big compared to the average difference between the overnight Eurodollar rate in London and the effective Fed funds rate, which is about 8 basis points. The spread can widen by several percentage points due to illiquidity or uncertainty. The spread may also be much smaller due to market conditions. Because of these reasons, the cost of using the

¹² The spreads of lending rates in the Eurodollar market typically range from slightly less than 1/2 of 1–3% and above, with the median being somewhere between 1% and 2%. The largest institutions sometimes manage to obtain funds at more favorable rates than the LIBOR.

knowledge of the predictable differential would outweigh the potential gain. A bank may be unwilling to pursue arbitrage except at a substantially enhanced spread.

6. Conclusion

There are a number of depository institutions which are free to trade funds in sufficient size in the Fed funds market and in the overnight Eurodollar market. Therefore, the Fed funds rate and the overnight Eurodollar rate are closely linked and the calendar day effects appear in both the overnight Eurodollar rate and in the Fed funds rate. However, the absolute magnitude of the calendar day effects on the overnight Eurodollar rate is slightly smaller than those on the Fed funds rate. The day-of-a-maintenance-period effect and the US holiday effect on the overnight Eurodollar rate is produced by characteristics in the Fed funds market, such as line limits, overnight overdraft penalties, transaction costs and weekend accounting conventions.

The differences between the Fed funds rate and the overnight Eurodollar rate can be predicted on the basis of lagged Fed funds rates, lagged overnight Eurodollar rates and calendar day dummies. Because of costs other than the interest rates, a bank which would expect the positive or negative spread does not or could not take arbitrage strategy.

Acknowledgements

I am especially indebted to James Hamilton for his very helpful discussion and suggestions. I also would like to thank Majorie Flavin, Wouter den Hann, Michelle Haynes, Garrett Jones, Tae-Hwan Kim, Paul Mizen and two anonymous referees for useful comments and James Jacobs for providing the data.

References

- Aliber, R.Z., 1980. The integration of the offshore and domestic banking system. *Journal of Monetary Economics* 6, 509–526.
- Allen, L., Saunders, A., 1992. Bank window dressing: Theory and evidence. *Journal of Banking and Finance* 16, 585–623.
- Campbell, J.Y., 1987. Money announcements, the demand for bank reserves, and the behavior of the federal funds rate within the statement week. *Journal of Money, Credit and Banking* 19, 56–67.
- Canova, F., Marrinan, J., 1995. Predicting excess returns in financial markets. *European Economic Review* 39, 35–69.
- Fama, E., 1965. The behavior of stock market prices. *Journal of Business* 28, 34–105.
- Flannery, M.J., Protopapadakis, A.A., 1988. From T-bills to common stocks: Investigating the generality of intra-week return seasonality. *Journal of Finance* 43, 431–450.
- French, K., 1980. Stock returns and the weekend effect. *Journal of Financial Economics* 8, 55–69.
- Fung, H.-G., Isberg, S.C., 1992. The international transmission of Eurodollar and US interest rates: A cointegration analysis. *Journal of Banking and Finance* 16, 757–769.

- Fung, H.-G., Lo, W.-C., 1995. An empirical examination of the ex ante international interest rate transmission. *The Financial Review* 30 (1), 175–192.
- Gibbons, M., Hess, P., 1981. Day of the week effects and asset returns. *Journal of Business* 54, 579–596.
- Griffiths, M.D., Winters, D.B., 1995. Day-of-the-week effects in federal funds rates: Further empirical findings. *Journal of Banking and Finance* 19, 1265–1284.
- Griffiths, M.D., Winters, D.B., 1997. On a preferred habitat for liquidity at the turn-of-the-year: Evidence from the term-repo market. *Journal of Financial Services Research* 12 (1), 21–38.
- Hamilton, J.D., 1996. The daily market for federal funds. *Journal of Political Economy* 104 (1), 22–56.
- Harris, L., 1986. A transaction data study of weekly and intradaily patterns in stock returns. *Journal of Financial Economics* 16, 99–117.
- Hendershott, P.H., 1967. The structure of international interest rates: The US treasury bill rate and the Eurodollar deposit rate. *Journal of Finance* 22, 455–465.
- Kaen, F.R., Hachey, G.A., 1983. Eurocurrency and national money market interest rates. *Journal of Money, Credit and Banking* 15, 327–338.
- Kamath, R., Whyte, A.M., Chatrath, A., Chaudhry, M., 1995. Daily seasonals in the Eurocurrency market. *American Business Review* 1, 1–7.
- Kwack, S.Y., 1971. The structure of international interest rates: An extension of Hendershott's tests. *Journal of Finance* 26, 205–224.
- Lakonishok, J., Maberly, E., 1990. The weekend effect: Trading patterns of individuals and institutional investors. *Journal of Finance* 45, 231–243.
- Levin, J.H., 1974. The Eurodollar market and the international transmission of interest rates. *Canadian Journal of Economics* 7, 205–224.
- Lo, A., MacKinlay, C., 1988. Stock market prices do not follow random walks: Evidence from a simple specification test. *Review of Financial Studies* 1, 41–66.
- Musto, D., 1997. Portfolio disclosures and year-end price shifts. *Journal of Finance* 52, 1563–1588.
- Nelson, D., 1991. Conditional heteroskedasticity in asset return: A new approach. *Econometrica* 59 (2), 347–370.
- Ogden, J.P., 1987. The end of the month as a preferred habitat: A test of operational efficiency in the money market. *Journal of Financial and Quantitative Analysis* 22 (3), 329–344.
- Reinhart, V., Harmon, R., 1987. The information structure of the overnight market. Manuscript.
- Saunders, A., Urich, T., 1988. The effects of shifts in monetary policy and reserve accounting regimes on bank reserve management behavior in the federal funds market. *Journal of Banking and Finance* 12, 523–535.
- Scholes, M., Williams, J., 1997. Estimating betas from nonsynchronous data. *Journal of Financial Economics* 5, 309–327.
- Spindt, P.A., Hoffmeister, J.R., 1988. The micromechanics of the federal funds market: Implications for day-of-the-week effects in funds rate variability. *Journal of Financial and Quantitative Analysis* 23 (3), 401–416.
- Stigum, M., 1990. *The Money Market*. Irwin Professional Publishing, New York.