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Yin-Wong Cheung

Hung-Gay Fung
fungh@umsl.edu

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Yin-Wong Cheung
and
Hung-Gay Fung

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Yin-Wong Cheung
Department of Economics
University of California
Santa Cruz, California 95064
Tel: (408) 459-4247
Email: cheung@cats.ucsc.edu

and

Hung-Gay Fung
School of Business Administration
University of Missouri-St. Louis
St. Louis, MO 63121-4499
Tel: (314) 516-6374
Email: fungh@msx.umsl.edu

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Abstract

A robust two-step procedure, which allows for both conditional mean and variance dynamics, is used to examine the pattern of information flows between the Eurodollar spot and futures markets. It is found that, after allowing for conditional heteroskedasticity, spot rates affect futures data and *vice versa*. In addition, there is evidence on volatility spillover between the two markets. Our results also indicate that information conveyed by data on futures tends to have a more persistent impact on both the mean and volatility of cash market price movements than the other way around.

Information Flows Between the Eurodollar Spot and Futures Markets

I. Introduction

Since its inception in the late 1950s, the Eurodollar market has become an important component of the international capital market. Multinational firms and financial institutions rely increasingly on the Eurodollar market for funds and interest rate information to evaluate, for example, costs of capital and interest rate movements (Melton and Pukula, 1984). The estimated market size grew from less than $1 billion in 1958 to about $4 trillion in the early 1990s. The rapid growth of the Eurodollar market is accompanied by that of Eurodollar futures. Eurodollar futures contracts, the most actively traded short-term interest contract, were introduced in December 1981 by the International Monetary Market in Chicago.

A major economic role of futures markets is the price discovery function; that is the ability to discover equilibrium prices in the present and in the future [Krehbiel and Adkins (1994), Hein and MacDonald (1993), Fama and French (1987), and Garbade and Silber (1983)]. A reason for prices to assimilate information faster in the futures market than in the spot market is that transaction costs in the former are lower. Also, the futures market is more liquid than the spot market. This suggests that futures prices can contain useful information on spot prices.

The existing empirical studies on information flows between the spot and futures markets typically examine the causality in the mean relationship between data on spot and futures prices. Recently, there is a growing literature on the relationship of conditional variances across financial markets and its implications on information transmission mechanisms; see, for example, Susmel and Engle (1994), Najand, Rahman, and Yung (1992), Baillie and Bollerslev (1991), and Hamao, Masulis and Ng (1990). Using a no-arbitrage model, Ross (1989) shows that information transmission is primarily related to the volatility of price changes. Engle, Ito, and Lin (1990) provide an alternative interpretation that relates information processing time to movements in variance. This development suggests price volatility has significant implications about information linkages between markets.

This study attempts to characterize the pattern of information flows using both price and volatility spillovers between the Eurodollar spot and futures markets. A two-step procedure proposed by Cheung and Ng (1996) is used to determine the mean and variance causal relationships. An advantage of the Cheung and Ng method is that it allows for both the conditional mean and variance dynamics in the testing procedure. Another attractive feature of the procedure is that its asymptotic behavior does not depend on the normality assumption, which is known to be violated by data on Eurodollar rates.

Specifically we examine the mean and volatility causation relationships between the Eurodollar spot and futures markets. Such information can be exploited to build a better model to describe both the conditional mean and conditional variance behavior. For practitioners, a better model of interest rate movements can lead to a better assessment of the interest costs of funding. Thus, a better understanding of the interest rate dynamics can lead to better interest rate risk management.

The paper is organized as follows: Section II presents a selected literature review. Section III discusses the data and presents some preliminary results. Section IV presents the causality test methodology and reports the estimated causality patterns of the Eurodollar spot and futures deposit rates. Some concluding remarks are offered in Section V.

II. Selected Literature Review

The pricing relationship between the cash and futures markets has been extensively examined in the literature. For example, Khoury and Yourougou (1991), MacDonald and Hein (1989), and Fama and French (1987) examine the price discovery function in various futures markets. Their results generally show that the futures market provides useful information about spot market price movements.

Some recent studies focus on the price interaction between cash and futures markets. Chan (1992) examines the intraday lead-lag relation between returns of the Major Market cash index, the Major Market index futures, and the S & P 500 futures. Stoll and Whaley (1990) analyze the contemporaneous correlation between the stock cash and futures indexes. The cointegration technique is also employed to investigate the empirical long-run relationship between spot and futures prices. For example, Tse and Booth (1997) use the cointegration framework to investigate the information transmission between the New York heating oil futures and London gas oil futures prices. Fung and Leung (1993) document that spot and futures prices are cointegrated in the

Eurodollar market, while Bessler and Covey (1991) find evidence of cointegration using price data on U.S. cattle.

Most empirical studies use return data to infer the information linkage between the cash and futures markets. However, as demonstrated by Ross (1989), return volatility provides useful information on information flow. Thus, data on return volatility in the spot and futures markets can provide information in addition to that available in the return data alone. Chan, Chan and Karolyi (1991) examine the intraday volatility relation between the stock cash index and its futures. Cheung and Ng (1996) develop a causality test based on cross correlation functions and apply the test to the 5-minute S & P cash and futures data. It is shown that information on causality in mean and in variance helps devise a better model to describe the temporal dynamics and the interaction of the S & P cash and futures data.

III. Preliminary Data Analysis

Daily data on the three-month Eurodollar spot rate and the nearby Eurodollar futures rate from January 1983 to July 1997 are used in this study. The spot rates are obtained from the Eurodollar market in London. The futures data are rates on a Eurodollar futures contract that calls for the delivery of a $1 million, three-month Eurodollar deposit. The Eurodollar futures trade on the International Money Market (IMM) of the Chicago Mercantile Exchange (CME). Eurodollar futures contracts are the most active interest rate instrument traded on CME. The data are obtained from datastream and contain 2634 observations.

A. Descriptive Statistics

Table 1 presents some descriptive statistics for the spot and futures data. All the skewness and kurtosis coefficients are significantly different from those of a normal distribution. Both spot and futures interest rates are extremely persistent, as indicated by the autocorrelation estimates $\rho(1)$ to $\rho(5)$. The Eurodollar spot rates, in both levels and first differences, tend to have a lower mean and variance than the futures rates. As indicated by the unit root tests reported below, the two interest rate series are better modelled as an integrated series. On the other hand, the differenced series exhibit weak correlation persistence.

The existence of unit root persistence is examined using the augmented Dickey-Fuller (ADF) test, which allows for both a constant and a time trend. The lag length parameter of the ADF test is determined using both the Akaike information criterion (AIC) and Schwarz Bayesian criterion (SBC). As shown in Table 1, the results based on both AIC and SBC indicate that the levels of both Eurodollar spot and futures rates are non-stationary, while their first differences are stationary.

The unit root test proposed by Kwiatkowski, Phillips, Schmidt and Shin (1992) (KPSS) is also applied to the data. The test is based on the assumption that the time series is the sum of either a mean or a deterministic trend, a random walk and a stationary error. It is a Lagrange Multiplier test for the null hypothesis that the error variance in the random walk component is zero. See KPSS (1992) for a more detailed discussion of the testing procedure. As shown in Table 1, the KPSS test results are consistent with those of the ADF test. Both spot and futures series are nonstationary while their first differences are stationary.

B. Results on the AR-GARCH model

Before discussing results on the interaction between Eurodollar spot and futures interest rates, we present some formal evidence on short-term dependence and conditional heteroskedasticity in these data. An AR-GARCH process is used to model interest rate dynamics because of its recorded success [e.g. Engle, Lilien and Robins (1987) and Chan, Karolyi, Longstaff and Saunders (1992)]. For a time series, {Z(t)}, t=1,..., T, an AR-GARCH process is given by

$$Z_t = c + \sum_{i=1}^{p1} a_i Z_{t-i} + \epsilon_t, \tag{1}$$

where $\epsilon_{t|t-1} \sim N(0, h_t)$,

$$h_t = \alpha_o + \sum_{i=1}^{p2} \alpha_i \epsilon_{t-i}^2 + \sum_{i=1}^{p3} \beta_i h_{t-i}. \tag{2}$$

Equation (1) describes the conditional mean dynamics. ϵ_t is the heteroskedastic error term with its conditional variance h_t given by equation (2).[1] p1, p2 to p3 are the lag parameters.

Results of fitting AR-GARCH models to the changes in the Eurodollar spot and futures interest rate data are reported in Table 2. Information criteria and diagnostic statistics are used to select the final models from various possible AR-GARCH specifications. The maximum likelihood estimates confirm both changes in spot and futures rate exhibit significant conditional heteroskedasticity. The fitted models indicate that the spot interest rate data have a more complex conditional mean and conditional variance dynamics. The Q(q) and $Q^2(q)$ statistics, which are calculated from the first q autocorrelation coefficients of the standardized residuals and their squares, suggest that the selected specifications explain the data pretty well.

Given the evidence of GARCH effects, the study of the interaction between the Eurodollar spot and futures interest rates should properly control for conditional heteroskedasticity. For instance, the presence of conditional heteroskedasticity may render the standard test for causality inefficient [Engle (1982)]. In addition, the GARCH specification provides a convenient framework to investigate volatility spillovers between Eurodollar spot and futures rates. The causality test results allowing for GARCH effects are discussed in Section IV.

C. Cointegration Analysis.

For a system of nonstationary series, the presence of cointegration among them has significant implications on modeling the dynamics of individual series. For instance, in the presence of cointegration, an error correction term should be included when one describes the time series behavior of the first differences of the series. As the Eurodollar spot and futures data used in this study may be cointegrated (see Fung and Leung (1993)), we have to determine whether an error correction term should be incorporated in the subsequent causality analysis. The Johansen (1991) procedure is used to test if cointegration exists between the spot and futures series. See Johansen

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[1] An EGARCH model can also be used to examine the information transmission problem. See Theodossiou (1994) and Koutmos and Theodossiou (1994) for the EGARCH model. Our model has a conditional normal distribution assumption. However, the test results of the causal pattern reported in Section IV do not depend on this normality assumption.

(1991) for a more detailed discussion of the test procedure.[2]

Table 3 reports the Johansen cointegration test results. The model used to conduct the cointegration test is quite adequate, as indicated by the Q-statistics. Both the maximum eigenvalue and trace statistics agree that there is (only) one cointegration relationship between the spot and futures series. The normalized cointegration vector (1, -0.9848) is not significantly different from (1, -1). Thus, the error correction term based on the difference between the spot and futures interest rates will be incorporated in the subsequent causality analysis.[3]

D. The Standard Granger Causality Test

We first apply the conventional Granger causality test to study the price interaction between the spot and futures markets. The Granger causality is determined using the equations:

$$\Delta S_t = c + \sum_{i=1}^{p1} a_i \Delta S_{t-i} + eE_{t-1} + \epsilon_{st}, \tag{3}$$

and

$$\Delta S_t = c + \sum_{i=1}^{p1} a_i \Delta S_{t-i} + \sum_{i=1}^{p2} b_i \Delta F_{t-i} + eE_{t-1} + \epsilon_{st}, \tag{4}$$

where S_t is the Eurodollar spot rate, F_t is the Eurodollar futures rate, E_{t-1} is the error correction term, ϵ_{st} is the regression error, and Δ is the differencing operator.

The ability of past ΔS_t 's to explain the current ΔS_t is captured by equation (3). The error correction term, which is constructed based on the difference between the spot and futures interest

[2] The Johansen procedure is more efficient than, for example, the two-step Engle and Granger approach. See, for example, Phillips (1991).

[3] We thank Geoffrey Booth for suggesting this specification of the error correction term. Results using the error correction term constructed from the estimated cointegration vector are qualitatively the same as those reported in the following sections.

rates, is included to capture the possible effects of deviations from the estimated long-run relationship. Information Criteria are used to determine the lag order parameters p1 and p2. ΔF_t is the change in the Eurodollar futures interest rate. The null hypothesis of futures data do not Granger cause spot data is rejected when b_i's, the coefficients of the lagged futures data, are not jointly insignificant. On the other hand, the hypothesis of spot data do not Granger cause futures data is tested using the following regressions:

$$\Delta F_t = c + \sum_{i=1}^{p1} a_i \Delta F_{t-i} + dE_{t-1} + \epsilon_{ft} \tag{5}$$

and

$$\Delta F_t = c + \sum_{i=1}^{p1} a_i \Delta F_{t-i} + \sum_{i=0}^{p2} b_i \Delta S_{t-i} + dE_{t-1} + \epsilon_{ft} \tag{6}$$

Results of testing the hypothesis of futures data do not Granger cause spot data are reported under the column labeled "SPOT" in Table 4. The lag order parameters p1 and p2 are determined sequentially using information criteria. The inclusion of lagged futures data improves the adjusted R-square, a measure of goodness of fit, almost by a factor of 4. The F-statistic of 253 suggests that coefficients b_i's are jointly significant -- that is, Eurodollar futures rates cause spot Eurodollar rates.

The results of testing the hypothesis of spot data do not Granger cause futures data are summarized under the column labeled "FUTURES" in Table 4. The F-statistic is 5.26. The spot Eurodollar rates have incremental explanatory power for the futures rates. That is, there is feedback between the spot and futures markets. However, the changes in adjusted R-squares suggest the futures market has a larger impact on the spot market than the latter one on the former.

IV. Causal Relationships

In this section we report causality test results based on the Cheung and Ng (1996) procedure, which test for causal relationships in the mean and in the variance. The test procedure is based on the standardized residuals and their squares estimated from individual AR-GARCH models. Using the notation in equations (1) and (2), the standardized residual is defined by $\epsilon_t/h_t^{0.5}$. Causality in mean is tested using cross correlation coefficients between standardized residuals, while causality in variance is investigated using the squares of standardized residuals.[4] It can be show that, under the no causality hypothesis, the cross correlation coefficients at different lags are independently and normally distributed in large samples. That is, there is no evidence of causality in mean (variance) when all the cross correlation coefficients calculated from (squares of) standardized residuals, at all possible leads and lags, are not significantly different from zero. The causality pattern is indicated by significant cross correlations. An appealing feature of the two-stage approach is that the asymptotic distribution of the test statistic does not depend on the normality assumption. This property is quite relevant for the current study since Eurodollar interest rates do not satisfy the normality assumption.

The cross correlation statistics computed from the standardized residuals from the fitted AR-GARCH models (reported in Table 2) are given in Table 5. The "lag" refers to the number of days that the spot data lag behind the futures data. The lead is given by a negative lag. Significance of a statistic with a positive lag implies the spot data cause the futures data. It is noted that data on Eurodollar spot and futures interest rates are not synchronized. The spot market in London closes before the opening of the futures market in the International Monetary Market. Thus, a lag-zero cross correlation, which measures the comovement in the same calendar day, should be interpreted as evidence that the spot interest rate causes the futures. The column labeled "LEVELS" gives the cross correlation statistics based on standardized residuals themselves. These statistics are for testing causality in the mean. Cross correlation statistics under the "SQUARES" column are based on the squares of standardized residuals and are used to test for causality in the variance.

Compared with the Granger causality test results reported in Table 4, cross correlation statistics reveal a more complex and dynamic causation pattern. For instance, the feedback effects in the means involve a higher order lag structure. Further, there is evidence that the causality in variance goes from the futures data series to the spot price series and *vice versa*. These results show that a proper account of conditional heteroskedasticity can have significant implications for the study

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[4] For an alternative approach to conduct causality test in a multivariate GARCH framework, see Theodossiou and Lee (1993).

of price and volatility spillovers. The information flows between the spot and futures markets affect not only price movements, but also volatility movements, in these two markets.

Cheung and Ng (1996) illustrate that the cross correlation statistics offer some useful information on the interaction between time series. Such information can be exploited to build a better model to describe the time series dynamics of the data. We adopted the following approach to extract the information from the cross correlation statistics computed from the Eurodollar spot and futures interest rates. Using the information in Table 5, we estimate an augmented AR-GARCH model for each interest rate series by incorporating the relevant lagged (and squared) data of the other series to its original AR-GARCH model reported in Table 2. Again, the error correction term is included to allow for the possible effect of deviations from long-run relationship.

Based on the estimation and diagnostic test results, we modify the augmented models until they pass Q and Q^2 tests. For the Eurodollar spot interest rate data, the resulting model is:

$$\Delta S_t = c + \sum_{i=1}^{p1} a_i \Delta S_{t-i} + \sum_{i=1}^{p2} b_i \Delta F_{t-i} + eE_{t-1} + \epsilon_{st}, \tag{7}$$

where $\epsilon_{st|t-1} \sim N(0, h_{st})$,

$$h_{st} = \alpha_o + \sum_{i=1}^{p3} \alpha_i \epsilon^2_{st-i} + \sum_{i=1}^{p4} \beta_i h_{st-i} + \sum_{i=1}^{p5} \delta_i \Delta F^2_{t-i}. \tag{8}$$

The augmented model for the futures data is

$$\Delta F_t = c + \sum_{i=1}^{p1} a_i \Delta F_{t-i} + \sum_{i=0}^{p2} b_i \Delta S_{t-i} + eE_{t-1} + \epsilon_{ft}, \tag{9}$$

$$h_{ft} = \alpha_o + \sum_{i=1}^{p3} \alpha_i \epsilon^2_{ft-i} + \sum_{i=1}^{p4} \beta_i h_{ft-i} + \sum_{fi=0}^{p5} \delta_i \Delta S^2_{t-i}. \tag{10}$$

where $\epsilon_{ft|t-1} \sim N(0,\ h_{ft})$,

The maximum likelihood estimates and the cross correlation statistics computed from the standardized residuals of the augmented models are given in Table 6 and Table 7, respectively. The added variables are significant, while the Q-statistics are not significant. The incremental explanatory power of the added variables is manifested by changes in the maximum likelihood values. The log likelihood increases from 4772 to 5207 for the spot series and from 3999 to 4288 for the futures data (see Tables 2 and 6). The results clearly indicate that there are feedback effects in both the mean and the variance. Further, the causation patterns revealed in the models in Table 6 are more complicated than those in Table 5. Nonetheless, data on futures still appear to have a more prominent impact on both the mean and the volatility of spot rates.

Comparing the results in Table 5 and Table 7, we observe that the interaction between the error terms of these two augmented AR-GARCH models, as indicated by the cross correlation statistics, is much weaker than that in the original AR-GARCH models. All the cross correlation statistics in Table 7 are insignificant. This result suggests that our augmented AR-GARCH model provides a good description of both the Eurodollar spot and futures deposit rate dynamics and the interaction between the two interest rate series.

The construction of the univariate augmented AR-GARCH models can be seen as the first step of building a bivariate model for the Eurodollar spot and futures interest rates. For instance, the lag structure uncovered in the augmented models helps determine the lag structure of the bivariate GARCH model. There is a strong justification to pursue a bivariate model even though one expects the causality pattern derived from the bivariate model will be similar to the pattern reported in Table 6. Theoretically, a correctly specified bivariate model will give a more precise description of the interaction between Eurodollar spot and futures rates. However, there appears to be a lack of consensus on the (asymptotic) behavior of the parameter estimates of a multivariate GARCH model [Engle and Kroner (1995, p. 141)]. As the distributional aspect of multivariate models is beyond the scope of the current paper, we leave the estimation and the subsequent statistical analysis of a multivariate model as a future research topic.

V. Concluding Remarks

This study examines the relationship between the three-month Eurodollar spot and futures interest rates during the period January 1983 to July 1997. The Cheung and Ng (1996) procedure, which is asymptotically robust to distributional assumptions, is employed to test for causality in both the mean and the variance. The observed causation pattern, which is controlled for both conditional mean and variance variations, indicates that there are feedback effects between the spot and futures markets. Movements in spot interest rates and their volatility tend to induce some fluctuations in futures data and *vice versa*. It is also found that the futures rate tends to have a stronger impact on the spot rate.

The causation patterns are in accordance with the price discovery function of a futures market. For instance the Eurodollar futures interest rate provides some incremental explanatory power for Eurodollar spot interest rate movements. Since both the futures and spot interest rates are associated with the same financial instrument, there is a strong theoretical reason to expect these two rates to be closely linked together. In fact, we found that the two interest rate series are cointegrated. As evidenced in Tables 4 and 6, the incremental information does not only come from lagged changes in futures rates, it also derives from the lagged spread between the spot and futures rates.
That is, it is not just the futures rate itself, but also its deviation from the spot rate contains useful information about variations in the Eurodollar spot interest rate. Further, the flow of information from the futures to the spot market is indicated by the causality in variance results.

The study of the dynamics of Eurodollar spot and futures rates can benefit significantly from a proper description of interest rate volatility. By explicitly modeling the conditional variance dynamics, we can easily investigate the possibility of volatility spillover and have a sharper inference on the price interactions in the spot and futures markets. Our results show that information flows between the spot and futures markets can be reflected in both price and volatility spillovers. Thus, the analysis of the pricing function should not be limited to the study of the relationship between the returns on the spot and futures markets.

In addition to the information flow pattern, the causality test yields valuable information on data dynamics. Such information can be exploited to build a better model to describe both the conditional mean and conditional variance behavior. Our estimation results strongly suggest that the information extracted from the causality tests can lead to dramatic improvement in the ability to explain interest rate dynamics. For practitioners, a better model of interest rate movements can lead to a better assessment of the costs of funding and capital budgeting. The conditional variance dynamics prescribed in the augmented AR-GARCH models may prove useful in the risk management exercise. Thus, a potential future research topic is to evaluate whether a better understanding of the mean and variance causality pattern helps improve interest rate risk management.

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Table 1: Descriptive Statistics for the Eurodollar Spot and Futures Interest Rates

	LEVELS		FIRST DIFFERENCES	
	SPOT	FUTURES	SPOT	FUTURES
Mean	6.875	7.032	-0.001	-0.001
Variance	4.878	5.086	0.006	0.009
Skewness	0.114	0.232	-0.527	1.588
Kurtosis	-0.709	-0.534	11.584	33.569
ρ(1)	0.999	0.999	-0.036	0.012
ρ(2)	0.998	0.998	-0.034	0.011
ρ(3)	0.998	0.997	0.021	0.007
ρ(4)	0.997	0.996	0.051	0.008
ρ(5)	0.996	0.995	-0.003	-0.014
ADF-AIC	-1.500	-1.804	-29.580*	-60.822*
	(5)	(1)	(4)	(1)
ADF-SBC	-1.461	-1.804	-63.795*	-60.822*
	(1)	(1)	(1)	(1)
KPSS-4	2.1574*	2.1593*	0.1088	0.0714
KPSS-8	1.0844*	1.0879*	0.1022	0.0721
KPSS-12	0.7269*	0.7309*	0.0966	0.0696

Note:

Skewness test statistic can be computed as $S_k[(N-1)(N-2)/6N]^{0.5}$ where $S_k=N^2m_3/[(N-1)(N-2)s^3]$. N is the number of observations, m_i is the ith moment and s is the standard deviation. Kurtosis statistic $=K_u\{[(N-1)(N-2)(N-3)/[24N(N+1)]\}^{0.5}$, where $K_u=N^2[(N+1)m_4-3(N-1)m^2_2]/[(N-1)(N-2)(N-3)s^4]$. ρ(k) gives the autocorrelation at lag k. ADF-AIC and ADF-SBC are the augmented Dickey-Fuller (ADF) tests with the lag order parameter chosen by the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (SBC). The lag parameter k used to perform the ADF test is given in the parentheses underneath the statistics. Critical values for the ADF test are from Cheung and Lai (1995). "*" indicates significance at the 5% level. KPSS-x is the KPSS statistic according to the x-rule. Both ADF and KPSS rules indicate that the spot and futures series are nonstationary and their first differences are stationary

Table 2. Maximum Likelihood Estimates of the AR-GARCH models.

	Spot	Futures
a_1	-0.0666 (-3.66)	0.0278 (1.92)
a_2	-0.0354 (-2.07)	
α_0	0.0096 (10.92)	0.0012 (16.89)
α_1	0.1016 (19.80)	0.0136 (30.17)
β_1	0.3197 (6.07)	0.9852 (21.18)
β_2	0.5664 (11.30)	
Log likelihood	4771.51	3999.36
Q(5)	10.4	1.63
Q(10)	13.2	8.92
$Q^2((5)$	5.11	3.03
$Q^2(10)$	8.31	4.13

Note:

The AR-GARCH model, $Z_t = c + \sum_{i=1}^{p1} a_i Z_{t-i} + \epsilon_t$, where $\epsilon_{t|t-1} \sim N(0, h_t)$, and

$h_t = \alpha_o + \sum_{i=1}^{p2} \alpha_i \epsilon_{t-i}^2 + \sum_{i=1}^{p3} \beta_i h_{t-i}$ is fitted to changes in Eurodollar spot and futures interest rates.

The reported models are selected based on information criteria and diagnostic checking results. The intercept term is insignificant and, therefore, excluded. α_0 is multiplied by a factor of 100. Q(k) and $Q^2(k)$ are the Ljung-Box statistics calculated from the first k autocorrelation coefficients of the standardized residuals and their squares. t-values are given in parentheses.

Table 3: Cointegration Test Results

		EI-STAT	TR-STAT
Null Hypothesis:	r = 0	73.9986*	75.6559*
	r = 1	1.6573	1.6573

Cointegrating vector = (1 -0.9848)

Q-statistics

	Spot	Futures
Q(5)	4.9225	0.8533
Q(10)	15.0410	12.6653

Note:
r is the number of cointegration vector. EI-STAT is the maximum eigenvalue statistic. TR-STAT is the trace statistic. Q-statistics give the Ljung-Box statistics calculated from the residuals of the estimated spot and futures interest rate equations. Q(k) is computed from the first k autocorrelations of the residuals. The maximum lag used in conducting the test, as selected by both the AIC and SBC, is three. Critical values are taken from Cheung and Lai (1993). Statistics significant at the 1% level is indicated by "*."

Table 4 Results of the Standard Granger-Causality Test

	SPOT		FUTURES	
c	-0.0093 (-6.46)	-0.0053 (-3.87)	0.0017 (0.96)	0.0017 (0.96)
e	-0.0540 (-11.84)	-0.0292 (-6.76)	0.0169 (2.96)	0.0163 (2.85)
a_1	-0.0414 (-2.59)	-0.1982 (-11.51)	0.0220 (1.35)	0.0052 (0.29)
a_2	-0.0394 (-2.47)	-0.0965 (-5.99)		
a_3	0.0068 (0.42)	-0.0096 (-0.64)		
a_4	0.0381 (2.38)	0.0391 (2.60)		
a_5	-0.0074 (-0.46)	0.0032 (0.22)		
a_6	-0.0409 (-2.57)	-0.0378 (-2.52)		
b_1		0.3032 (22.34)		0.0594 (2.86)
b_2		0.0978 (6.85)		0.0335 (1.70)
Adjusted R-SQUARE	0.0402	0.1538	0.0019	0.0042
F-Statistic		254.7554		5.2805

Note:
The models for testing the hypothesis of futures data cause spot data are:

$$\Delta S_t = c + \sum_{i=1}^{p1} a_i \Delta S_{t-i} + eE_{t-1} + \epsilon_{st},$$

$$\Delta S_t = c + \sum_{i=1}^{p1} a_i \Delta S_{t-i} + \sum_{i=1}^{p2} b_i \Delta F_{t-i} + eE_{t-1} + \epsilon_{st},$$

where ΔS_t is the change in the spot interest rates and ΔF_t is the change in the Eurodollar futures rates. E is the error correction term. To test the hypothesis of spot data cause futures prices, we interchange the roles of ΔS_t and ΔF_t to test the Granger causality hypothesis.

The lag parameters p1 and p2 are determined sequentially using the AIC criterion. The "F-statistic" row gives the F-statistic for the null hypothesis of the b_i coefficients are jointly insignificant in the Granger-causality model. The null is rejected at the 1% level in both cases.

Table 5. Cross-Correlation Analysis for the Levels and Squares of the Standardized Residuals

Lag k	LEVELS	SQUARES
-10	-0.9280	0.9557
-9	0.9910	1.1794
-8	-0.4782	-0.7097
-7	1.4489	-1.3202
-6	0.8069	0.5373
-5	2.5736*	0.9034
-4	0.6024	-0.2340
-3	2.0112*	-0.6135
-2	4.9757*	0.3167
-1	19.9032*	4.0912*
0	16.4739*	6.4721*
1	2.7537*	-0.6996
2	1.8551	-0.2661
3	0.8774	2.5375*
4	-0.6095	-0.3607
5	1.8631	1.0162
6	0.3628	0.8174
7	0.2965	-1.0101
8	-1.3146	0.3925
9	0.8683	0.6912
10	0.4562	0.6928

Note:
Sample cross-correlation statistics are calculated from standardized residuals (column "LEVELS") and their squares (column "SQUARES") obtained from models reported in Table 2. "Lag" refers to the number of days the spot data lag the futures data. A lead is given by a negative lag parameter. "*" indicates significance at the 5% level.

Table 6: Augmented AR-GARCH Models for the Eurodollar Spot and Futures Interest Rate Data.

	SPOT	FUTURES
a_1	-0.2515 (-14.37)	-0.0991 (-6.37)
a_2	-0.1120 (-6.41)	-0.0485 (-2.54)
e	-0.0349 (-7.40)	0.0146 (2.57)
b_0		0.4113 (16.58)
b_1	0.4155 (26.18)	0.1209 (5.06)
b_2	0.1278 (8.21)	0.0666 (3.08)
b_3	0.0538 (3.36)	0.0141 (0.77)
α_0	0.0054 (9.99)	0.0014 (8.99)
α_1	0.0567 (12.96)	0.0011 (12.23)
β_1	0.9071 (19.97)	0.0062 (13.88)
δ_0		0.2440 (19.43)
δ_1	0.1354 (12.58)	-0.2318 (-18.01)
δ_2	-0.1150 (-12.70)	
Log Likelihood	5207.31	4287.88
Q(5)	7.75	3.00
Q(10)	12.30	16.50
$Q^2(5)$	5.80	1.78
$Q^2(10)$	8.66	2.94

Note:

An augmented model, $\Delta S_t = c + \sum_{i=1}^{p1} a_i \Delta S_{t-i} + \sum_{i=1}^{p2} b_i \Delta F_{t-i} + eE_{t-1} + \epsilon_{st}$, where

$\epsilon_{st|t-1} \sim N(0, h_{st})$, and $h_{st} = \alpha_o + \sum_{i=1}^{p3} \alpha_i \epsilon_{st-i}^2 + \sum_{i=1}^{p4} \beta_i h_{st-i} + \sum_{i=1}^{p5} \delta_i \Delta F_{t-i}^2$, is fitted to the Eurodollar

spot data. ΔS_t and ΔF_t are, respectively, changes in the Eurodollar spot and futures interest rates. E is the error correction term constructed based on the difference between the spot and futures rates.

The model for the futures data is

$\Delta F_t = c + \sum_{i=1}^{p1} a_i \Delta F_{t-i} + \sum_{i=0}^{p2} b_i \Delta S_{t-i} + eE_{t-1} + \epsilon_{ft}$, where $\epsilon_{ft|t-1} \sim N(0, h_{ft})$, and

$h_{ft} = \alpha_o + \sum_{i=1}^{p3} \alpha_i \epsilon_{ft-i}^2 + \sum_{i=1}^{p4} \beta_i h_{ft-i} + \sum_{i=0}^{p5} \delta_i \Delta S_{t-i}^2$.

The reported models are selected based on estimation and diagnostic checking results. α_0 is scaled by a factor of 100. Q(k) and $Q^2(k)$ are the Ljung-Box statistics calculated from the first k autocorrelation coefficients of the standardized residuals and their squares. t-values are given in parentheses.

Table 7. Cross-Correlation Analysis for the Levels and Squares of Standardized results from the Augmented AR-GARCH Models reported in Table 6

Lag k	LEVELS	SQUARES
-10	-0.4576	-0.7081
-9	-0.4024	0.1742
-8	-1.7928	-0.2588
-7	0.9947	-1.2815
-6	1.2909	-0.4800
-5	1.8569	-0.4425
-4	0.2420	-0.9080
-3	-0.0337	-0.7720
-2	0.3602	0.0039
-1	-0.4524	0.4296
0	0.6571	0.3906
1	1.2581	-0.6312
2	1.4348	-0.4807
3	1.1826	0.0512
4	-0.0292	-0.5135
5	1.0541	0.5574
6	-0.3846	0.5717
7	0.8570	-1.1978
8	0.0776	-0.8081
9	1.1758	-0.1216
10	0.7525	1.6828

Note:
Sample cross-correlation statistics are calculated from standardized residuals (column "LEVELS") and their squares (column "SQUARES") obtained from models reported in Table 6. "Lag" refers to the number of days the spot data lag the futures data. A lead is given by a negative lag parameter. No coefficient estimate is significant at the 5 % level.