Options on Fed Funds Futures and Interest Rate Volatility

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ABSTRACT

I examine the impact of listing options on the Fed Funds futures on the level and the conditional volatility of the Fed Funds spot and futures markets. The introduction of options leads to a lower conditional volatility in the underlying interest rates, suggesting that options on futures stabilize the primary markets. The effects of option introductions are not, however, uniform across several related interest rates. In some cases, options introduction is associated with a small but economically significant increase in the conditional volatility of interest rates.

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I thank David Simon for helpful suggestions. I am responsible for all remaining errors.

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I. Introduction

The effects of options and futures trading on underlying markets have generated a number of academic studies. The primary focus in these studies is whether derivatives stabilize or destabilize the primary market, and to a large extent, this is an empirical issue because anything is possible. For example, Harris (1989) notes that an increase in informed trading can either increase or decrease volatility of the primary market depending upon how the introduction of derivatives affects uninformed traders, order flow imbalance, introduction of new information, liquidity injection, and introduction of noise. One strand of the literature posits that if derivatives become substitutes for primary securities then the volume of trading in the primary market may decline. Stein (1987) claims derivatives markets could actually destabilize the primary market by reducing social welfare and by encouraging speculation. In another strand of the literature, it is argued that derivatives allow informed traders to shift risk to uninformed traders and are essential for stabilizing the primary markets (Grossman, 1988). Naturally, one would expect the volatility of the primary market to decline.

Another important reason for the volatility of the primary markets to change stems from the way options are hedged in the primary market. This is known as the 'feedback effect' of dynamic hedging behavior of options dealers. See Platen and Schweizer (1998), Frey and Stremme (1997) and Pearson, Poteshman, and White (2007) for more. Basically, options dealers usually delta-hedge their options positions by buying and selling the underlying stocks, so, in order to be delta-neutral, the option writer must buy the underlying stock when the stock price rises and sell stock when the stock price falls. The option buyer's behavior is exactly opposite. Since purchased options positions have positive gammas, they are dynamically hedged by selling the stock when the price rises and buying the stock when the price falls. If the aggregate gamma in the market is positive then delta-hedging (selling if the stock price increases, and buying if it decreases) has the potential to reduce the volatility in the primary market (Pearson, Poteshman, and White (2007)).

This study is the first of its kind at providing an analysis of the impact of the introduction of options on Fed Funds futures on the volatility in underlying markets: the Fed Funds spot and Fed Funds futures. Since their introduction on March 14, 2003, CBOT options[1] on the Fed Funds futures have become increasingly popular[2] for risk management. The possibility that the volatility in the primary markets may rise or fall stems from the way options are hedged in the primary markets. For instance, if options dealers delta-hedge their options positions by buying and selling Fed Funds futures, increased trading activity can have a direct effect on the volatility of these markets. Based on a multivariate GARCH error correction model, I examine if there are differences in the way spot and futures markets react to options introductions. Furthermore, I also examine the response of two related markets—the Eurodollar and the Libor spot and futures– to the introduction of options on Fed Funds futures. Both of these popular interest rate markets are closely related to the Fed Funds market. An evidence of an increase in trading activity and a decrease in volatility would be consistent with the notion that derivative securities are important innovations for increasing liquidity and reducing volatility of underlying and related markets.

I also investigate the response of several popular short-term interest rates to the introduction of options on Fed Funds futures. According to the CBOT, interest rate exposure due to changes in

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[1] CBOT options on Fed Funds futures (ticker symbols FFC (call) and FFP (put)) are American options for one unit of Fed Funds futures. Currently, monthly contracts are available for up to two years. The minimum tick size is one quarter basis points which is equivalent to $10.4175.

[2] According to the CBOT, the daily volume of options on Fed Funds futures was approximately 21,908 on March 30, 2007. The CBOT also introduced a new option contract called Fed Binary Options which pays either 0 or the intrinsic value of the option. On February 7, 2007, open contracts in Binary options exceeded the previous record of 19,358 contracts set in September 2006. The February figure for the total number of open contracts was 20,798 (Reuters, February 8, 2007).

the repo rate, the commercial paper, mortgage rates, treasury rates, government bonds yields, and swaps can be hedged using Fed Funds futures and options. Naturally, an introduction of options on Fed Funds futures may affect on these related markets.

The study is organized as follows. In Section II, I briefly survey the effects of derivatives on the primary markets. The discussion begins with an analysis of the impact of futures listing on the underlying markets, followed by a discussion of the effects of options listings. In Section III, I discuss the empirical results. The final section offers conclusions.

II. Derivatives Listing and Volatility in Primary Instruments

The literature is replete with a large number of studies on the relationship between derivatives trading and primary market volatility. Clifton (1985) examines the effects of listing currency futures and finds that the spot market volatility increases for major currencies. Edwards (1988) examines the impact of an introduction of futures on stock index and finds that futures-listing is associated with a decline in the volatility of the stock index. Bessembinder and Seguin (1992) find that the introduction of futures on stock index markets is associated with lower volatility in the equity market. Jochum and Kodres (1998) examine the impact of the introduction of futures on Mexican peso and find that spot market volatility is lower following the introduction of futures. In addition, the authors find no significant effect on two emerging market currencies: the Brazilian real and the Hungarian forint. Finally, Becketti and Roberts (1990) find that the stock market volatility did not increase due to futures trading. In contrast, Chatrath, Ramchander, and Song (1996) find an increase in spot exchange rate conditional volatility for the British pound, the yen, Canadian dollar, Swiss franc and the Deutsche mark following an introduction of futures on currencies. Gulen and Mayhew (2000) examine the effects of index futures listings in 25 countries and find that post-listing volatility is higher only in the US and in Japan. Ely (1991) finds that listing of interest rate futures has no effect on the underlying markets. Koutmos and Tucker (1996) offer evidence that futures on S&P500 lead to a higher volatility in the S&P500 spot market. Overall, the evidence is mixed. See Bhargava and Malhotra (2007) for additional studies and Jochum and Kodres (1998) for an excellent survey.

With regard to options listings effects, there are three distinct strands of the literature. In the first strand, opponents argue that options may act as substitutes for the underlying security, and divert trading volume away from the primary market into the options market. As a result, the introduction of options would have a detrimental impact on the liquidity and the volatility of the underlying asset market. Several empirical studies on options introductions have confirmed an increase in volatility of underlying instruments following options listing. Heer, Trede and Wharenburg (1997) find the volatility of the underlying stocks increases after options on the stocks were listed. Mayhew and Mihov (2000) find that options-listing is associated with an increase in volatility.

The second strand of the literature emphasizes the informational efficiency of the options market. Proponents of options argue that since markets are incomplete, the introduction of options makes the market more complete. This, in turn, improves the liquidity in the underlying asset market, and has a stabilizing effect[3] on underlying asset prices[4]. According to Grossman (1988), option prices reveal information about the underlying markets. As investors dynamically hedge their options position by buying and selling underlying assets, volatility may actually decline. Because of this information aggregation, which is revealed through prices, the market becomes informationally efficient. However, Stein (1987) claims that if information from the options market contaminates the information content in the underlying market then volatility may actually rise. Figlewski and Webb

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[3] Telser (1981) presents a similar view with respect to the impact of the introduction of futures on commodities. He suggests that futures markets evolve over time due to adaptation and need for risk management. Therefore, an introduction of futures could have feedback effects on the spot market. Furthermore, Telser compares futures with forward contracts and suggests that the standard deviation of forward price movements would be higher without futures contracts which enhance market liquidity.

[4] See Ross (1976), Hakansson (1982) and Grossman (1988).

(1993) suggest that options may actually improve the welfare of traders who could not conduct short sales earlier, thus, option trading improves both transactional and informational efficiency in the stock market. Diamond and Verrecchia (1987) also suggest that short sell restrictions can be circumvented by trading options. As a result, their model predicts that options introduction can attract more informed trading and increase informational efficiency of the primary market. This is also noted by Cao (1999) who shows that options listing leads to an increase in the amount of information collected on the primary assets. Cao suggests that by aggregating information, prices become more informative and they end up being higher and the volatility reduced. Ross (1976) suggests that trading in options can improve pricing efficiency in the equity markets by eliminating noise.

Several researchers find evidence that compared to nonoptioned stocks, post-listing volatility for optioned stocks is lower. Detemple and Jorion (1990) document an increase in the stock price of the underlying firms' as well as a decrease in volatility in response to options listing. Similarly, Conrad (1989) finds that option listings for 97 firms are associated with an increase in the stock price and a decrease in the volatility. Damodaran and Lim (1991) find a decrease in stock volatility following options listing. Bansal, Pruitt and Wei (1989) claim that option listing leads to a reduction in the total risk of firms with options. Jennings and Stark (1986) suggest that options allow quick dissemination of earnings news in the market. Shastri, Sultan, and Tandon (1996) use a bivariate GARCH error correction model to examine the effects of options on foreign currencies. They find that options introductions had no effect on the conditional mean returns in the currency market but the conditional volatility actually declined. Pearson, Poteshman, and White (2007) find evidence that options listings effects are largely due to the way options trader hedge their positions using the underlying stocks. Based upon daily data on all equity options traded on CBOE during 1990-2001, the authors offer evidence of an increase in volatility due to options trading. As a measure of robustness, the authors conclude that the documented effect is not driven by options expiration phenomena.

The final strand of the literature questions the reliability of the listing effects documented in earlier studies. For example, Bolen (1998) and Freund, McCann, and Webb (1994) claim that since options are introduced for stocks with high variance, options listing on these stocks tend to reduce the volatility. In fact, using a controlled sample, the authors find that a reduction in variance, following options listing, is also evident in stocks without options. So, it is not surprising that options listings lead to lower volatility. Another potential problem with options listings studies is that they do not control for market-wide decline in volatility around the time when options are listed. Lamoureux and Pannikath (1994) control for market-wide decline in volatility around options listings and find that options listing did not reduce volatility in the primary market. Krauss and Zimmerman (2001) find evidence that options listing on Swiss equities lead to ambiguous effects on the primary market. Similarly, Kelmkovsky and Maness (1980) found ambiguous effects of option listing on the beta and volatility of stocks. Freund, McCann, and Webb (1994) show that options listings are associated with lower volatility for only for the first batch of options introductions. Later introductions of options were not associated with a decline in the volatility of the optioned stocks.

Overall, options and futures affect the primary markets for a variety of reasons including price discovery, informational efficiency, shifting risk from informed to uninformed traders, speculation, and risk management through delta hedging. In general, there is evidence to suggest that primary market volatility decreases and liquidity improves after options listing, with delistings having the opposite impact on volatility and liquidity[5].

With respect to the effects of options introduction on Fed Funds futures, there has not been

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[5] See, for example, Conrad (1989), Skinner (1989), Damodaran and Lim (1991), DeTemple and Jorion (1990), Schultz and Zaman (1989), Fedenia and Grammatikos (1992), Hingorani, Jayaraman and Shastri (1993), Kumar, Sarin and Shastri (1998) and Seth and Venkatesh (1993).

any study conducted to examine how the primary markets have been affected. In particular, if options are delta-hedged in the primary markets, it would be interesting to learn if options on Fed Funds lead to a reduction in the volatility of primary markets. Furthermore, the effects of options introductions may also affect other short term interest rates such as the Eurodollar, Libor, commercial paper rates, the repo rate, interest rate swap spreads, government and corporate bond yields. These markets tend to follow innovations in the Fed Funds markets. In particular, interest rate exposure in these markets can be hedged using the Fed Funds options and futures contracts. Therefore, we may expect to find some evidence of the effects of options on Fed Funds futures on the level and volatility of these interest rates. In the next section I discuss the Fed Funds markets and develop an empirical model to test the effects of options listing on primary markets.

c. The impact of introduction of options on Fed Funds futures on underlying instruments

A quick review of the Fed Funds market is in order to examine the impact of Fed Funds futures options listings. In the United States, all commercial banks are required to hold reserves at the Fed. A commercial bank can raise required reserves when it fails to meet the Fed's reserve requirement, for example, by liquidating existing portfolio investment, borrowing excess reserves (the rate charged is known as the Federal Fund rate) in the reserves market, and borrowing from the Fed. The Fed uses the Fed Funds rate to control liquidity in the market. For example, the Fed reduces the supply of reserves by conducting open market sale of securities when the Funds rate target is raised. In contrast, when the Funds rate target is lowered, the Fed is believed to have been conducting open market purchase of securities which adds reserves to the banking system and subsequently leads to lowering of the Fed Funds rate (Taylor, 2001). Since long-term interest rates are based upon the average expected level of the Fed Funds spot rate over the relevant holding period, the Fed Funds spot rate should offer some hints on future monetary policy.

The CBOT 30-day Fed Funds futures contract calls for delivery of the interest paid on $5 million overnight Fed Funds held for 30 days. The contract is cash settled against the monthly average of the daily Fed Funds effective rate. Currently, one through five-month contracts are traded, in addition to a 'spot' month contract that is based on average Funds rate in the current month. Since its introduction, the Fed Funds futures contracts have become popular for hedging, speculation, as well as for predicting Fed policy outcomes. As Carlson, Melick, and Sahinoz (2003) claim, the Fed Funds futures rate is based upon a 'deliberative' policy outcomes of the Fed because on average the Fed Funds rate moves in tandem with the target Fed Funds rate. Since the target Fed Funds rate is effectively managed by the actions of the FOMC, the Fed Funds futures provides quite a reasonable estimates of the policy outcomes on average.

Unfortunately, the Fed Funds futures supplies the market with only two outcomes, the probability of a rate increase and the probability of a rate cut. In essence, the futures contracts do not offer useful information to capture the entire distribution of the expectations about the Fed Funds rate. According to Carlson, Craig, and Melick (2005), if the market participants have a wide range of expectations on the next policy outcomes, the Fed Funds futures cannot accurately incorporate such expectations.

American style options on CBOT Fed Funds futures add to the collection of risk management tools for those with an exposure to interest rate volatility. A call option on the Fed Funds futures gives the buyer the right to establish a long position in the Fed Funds futures. So, if one expects the Fed to raise the target Fed Funds rate, then a profitable strategy would be to buy a put option. The strike prices are set around the previous day's closing price for the futures contract. So, there would be 21 strike prices around this price at 6.25 basis points intervals. In addition, there would be 10 more strike prices outside of the band (5 increments of 12.50 basis points above the

Fed Funds futures price and 5 decrements of 12.50 basis points below the Fed Funds futures price). Options are quoted with a quarter basis points tick size, which is worth $10.4175.

As suggested earlier, the most direct link between the Fed Funds options markets and other short term interest rates is a result of how interest rate options dealers hedge their interest rate risk in the primary markets. First, dealers calculate the delta of their portfolio which contains written options and then add an offsetting position in the underlying market to make the aggregate portfolio delta equal to zero. So, if a dealer has sold calls, which has a negative delta, an increase in the underlying will push the call into moneyness. To protect his position, the dealer buys the underlying spot instrument when the price rises and sells the underlying when the price falls. Kambhu (1998) claims that to hedge against interest rate movements, dealers must continuously make adjustments in their portfolio by buying and selling the underliers. This is the framework where dealer's additional demand for spot instruments leads to further changes in the prices of the spot instruments. According to Kambhu (1998), this feedback mechanism suggests that "dynamic hedging would have the potential to amplify the volatility of asset prices when prices fall abruptly."

As noted earlier, the Fed Funds futures contracts provide the market with only two outcomes on the expected Fed decision. In contrast, options on Fed Funds futures can offer to the market participants the probability density function for the target path of the Fed Funds rate. See Carlson, Craig, and Melick (2005) for a convenient framework to extract the probability density function from the Fed Funds options prices. Viewed in this manner, options on CBOT Fed Funds futures can help one to speculate on the likelihood of future monetary policy and in particular the amount of the Fed's interest rate adjustments. According to the Chicago Board of Trade, "It can also be used in a variety of risk management applications. Financial market participants who can benefit from using these options include, but are not limited to, bond traders, hedge fund managers, portfolio managers, corporate treasurers, and bank investment managers."[6]

From the CBOT brochure, it is evident that options listing should have a direct effect on some of the interest rate futures and interest rates that are routinely used by portfolio managers, traders, bond dealers, and Fed Funds traders. For example, commercial paper traders and portfolio managers hedge their positions in the commercial paper market using options on Fed Funds futures. This allows them to manage the short term interest rate risk by betting on the basis risk between commercial papers and the Funds rate. Government securities traders can also use options on the Fed Funds to mitigate risks from changes in the yield curves. Bond dealers also use options on the Fed Funds futures to manage risks of shifts in the yield curve in response to changes in the Funds rate. Eurodollar and Libor traders can also make directional bets on the market and hedge some of the risks by taking positions in the Fed Funds options market. Finally, swap dealers can also hedge their position mismatch in the interest rate swap market by using CBOT options on the Fed Funds futures. Overall, any interest rate cash and futures, commercial paper rates, mortgage rates, treasury rates, bond yields,

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[6]**Potential Users of Options on CBOT Fed Funds Futures:**
According to the CBOT, the Fed Funds futures options are attractive to a variety of traders and investors. "*Commercial paper issuers:* Companies that routinely issue large quantities of commercial paper can reduce their financing costs by writing call options on CBOT Fed Funds futures against the paper they anticipate issuing, given an opinion on volatility that makes this feasible. This can reduce the cost of issuance by the amount of premium collected on calls. Or it can transform outright short-term rate risk to basis risk between commercial paper rates and the Funds rate. *Portfolio managers:* Institutional investors who hold large amounts of commercial paper and who see a favorable outlook for Fed Funds volatility can write calls against their holdings with an eye to enhancing returns. This strategy is roughly analogous to a covered call writing strategy in the equity and equity option markets. *Matched book traders:* Dealers in government securities often run large matched books and make loans or borrow money using government securities as collateral. The benchmark rate for these transactions is the Fed Funds rate. Matched book traders can use options on CBOT Fed Funds to balance exposure on either side of the market or to hedge exposure to financing tails. *Bond dealers:* Bond dealers finance their inventories (both long and short) against the Fed Funds rate. In addition, bond basis and yield curve trading strategies are highly sensitive to the Funds rate. Bond dealers can use options on CBOT Fed Funds both to manage risks from shifts in the yield curve and to manage the costs of financing basis trades. *Hedge fund managers and proprietary traders:* Relative value traders who use Eurodollar options to express views on LIBOR volatility can use those options in combination with options on CBOT Fed Funds futures to trade differentials between these two volatility markets. *Interest rate swap users:* Users of interest rate swaps must often deal with timing mismatches between the swap and the hedge instruments they use. These market users will find that options on CBOT Fed Funds futures can help them control that stub risk. *Foreign Exchange Dealers:* Because interest rate differentials are a key determinant of currency rates, foreign exchange dealers have many potential uses of options on CBOT Fed Funds futures. Conservative users can use options on CBOT Fed Funds futures to manage the spread between spot and forward rates. Because currency rates are sensitive to changes in interest rate differentials, currency speculators can use options on CBOT Fed Funds futures to express a view on Federal Reserve monetary policy." CBOT Brochure on options of Fed Funds futures, 2003.

and swap rates may be sensitive to options on CBOT Fed Funds futures. In the empirical section, I will examine the effects of options listing on the Fed Funds spot and futures markets, as well as several related interest rates such as the Libor, the Eurodollar, the commercial paper rate, the repo rate, the Treasure bond rate, interest rate swaps, corporate bond yields, and mortgage rates.

III. The Data and Empirical Methods

Data on all spot interest rates and interest rate futures contracts are obtained from the Datastream. To be consistent with studies involving financial futures and options, I will be using the most nearby futures contracts. Several diagnostic checks on the distributions of the interest rates, volume, and open interest will be presented. These tests include univariate descriptive statistics, the Bera-Jarque statistics for detecting non-normality. I also use the Engle's LM test (Engle, 1982) to determine if spot and futures interest rates distributions are time varying. Finally, the Engle and Granger (1987) test for cointegration between the spot and the futures will be performed to determine if there is a fundamental relationship between them[7].

In Table 1, diagnostic statistics are reported. The daily Fed Funds spot rate is a simple yield to maturity expressed in percent. The daily Fed Funds futures rate is the simple add on yield (100- futures price). All variables are converted into changes in log of the daily values. In Panel A, I find that the changes in the daily spot rate and the daily Fed Funds futures rate are non-normal. The skewness for the spot market is negative while for the futures market it is positive. Both variables have excess kurtosis. The Jarque-Bera statistic, a test of goodness of fit based upon skewness and kurtosis, confirms that these variables are not normally distributed. The Ljung-Box statistic with 24 degrees of

[7] Brenner and Kroner (1995) suggest that cointegrated variables are linked to one another in a fundamental way such that in the short run they may deviate from each other but in the long run they are held together in a steady-state equilibrium. In the futures markets, the cost-of-carry theory suggests that cash and futures prices are related such that arbitrage activity will force them to move within the no-arbitrage bound. The error correction term can be thought of as measuring the impact of arbitrage opportunities on interest rates. Intuitively, the coefficient measures the degree to which each market is responsible for restoring the non-arbitrage equilibrium

freedom shows that there is serial correlation in both variables. Finally, the presence of ARCH effects is confirmed by Engle's TR^2 statistic with 24 lags, suggesting that variances are changing over time.

It is well known that daily changes in the Fed Funds spot and futures exhibit day of the week effects, especially on Wednesdays when reserves settlement are carried out by the Fed. In addition, the market was closed in the aftermath of the 9/11 terrorist attack in the US. Finally, changes in the Fed's target rate for the Fed Funds market should also be stylized determinants of the spot and the futures markets since they move in tandem with the Fed's policy actions. To account for these known stylized facts, I estimated two ARIMA models with the following factors: the day of the week dummies, the 9/11 attack dummy (which takes a value of 1 after the 9/11 attack, and zero otherwise), and changes in the Fed's target rate. The predicted values of the dependent variable in each case are used in subsequent regressions[8]. The results from estimating ARIMA models are reported in Panel B. First, the 9/11 attack dummy is negative and significant for both markets. It is not surprising that the 9/11 dummy is larger in the spot rate equation, an indication that there was a massive liquidity injection by the Fed following the 9/11 attack to ensure the stability of the market. As expected, changes in the target rate are significant in both markets. The slope coefficient is positive in both instances and the effects are larger in the spot market than in the futures market, which is to be expected.

In Panel C, diagnostic statistics for the fitted values of the dependent variables are shown. Based upon skewness, kurtosis, and the Jarque-Bera, daily changes in the spot rate are not normally distributed. The Ljung-Box indicates that the hypothesis of no serial correlation can be soundly rejected. Finally, the Engle's TR^2 shows that the volatility of each fitted variable is time dependent.

There is an additional diagnostic that must be performed before estimating GARCH models.

condition implied by the cost-of-carry.

[8] All subsequent interest rates and futures yields used in this paper are predicted values from ARIMA regression with 9/11 atack

Since the spot and the futures markets are closely related, it is possible that they are cointegrated. In Panel D, the results of the cointegration tests are reported. First, the Dickey-Fuller test statistic, with an intercept and a trend, for the spot rate is -.46, while for the futures rate, it is -.44, indicating that the variables are non-stationary in the levels. While these two variables may be non-stationary in the levels, errors from a linear combination may be stationary, thus confirming cointegration. The results indicate that the variables are indeed cointegrated. The augmented Dickey-Fuller test statistic is -7.37, which implies that any regression model of either the spot rate or the futures rate must also include the error correction term (ECM) as an exogenous variable.

Before estimating the multivariate GARCH models, it is important to examine if univariate GARCH models are sufficiently adequate to document the effects of options listing on the primary markets. The univariate GARCH model is of the following type:

(12) $$\Delta \ln S_t = \delta_0 + \delta_1 ECM_{t-1} + \delta_2 Listing + \varepsilon_t$$

(13) $$\varepsilon_t \,|\, \psi_{t-1} \sim N(0, \sigma_t^2),$$

(14) $$\sigma_t^2 = \Omega + \sum_{i=1}^{q} \alpha_i \varepsilon^2_{t-i} + \sum_{j=1}^{p} \beta_i \sigma_{t-j} + \phi_1 ECM_{t-1} + \phi_2 Listing$$

where S_t in the mean equation (12) is the daily changes in the predicted Fed Funds spot rate. ECM_{t-1} is the error correction term between the spot and the futures markets and Listing is a dummy variable that takes the value of 1 on the day options on Fed Funds futures started trading, and 0 otherwise. The variance equation (14) models the conditional variances as a GARCH(p,q) process where p and q denote the lag length. Ω is the intercept term, α_i are ARCH terms and β_j are GARCH terms.[9] The α and β terms are expected to be positive and significant determinants of the conditional variance of changes in the spot rate. Notice that the exogenous variables are also

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dummy variable, changes in the Fed's target rate, and day of the week dummies as exogenous variables.

included in the conditional variance equation to examine their effects on volatility.

The univariate GARCH regressions are estimated with robust standard errors. The results are reported in Table 2. The results for the Fed Funds spot and the futures markets are reported, followed by the results for the Eurodollar and the Libor markets. For the Fed Funds spot and the futures markets, the error correction term (ECM_{Fed}) has a negative and significant coefficient, suggesting that a deviation from the futures market causes both markets to revert to their long-run relationship. The options listing dummy variable has a negative effect on the Fed Funds spot rate and the coefficient is significant at the 1% level. In contrast, the option listing dummy variable has a positive effect on the Fed Funds futures market. An increase in the daily futures rate could be consistent with the notion that derivatives products stimulate demand in the primary market. In addition, this additional demand may also be reflecting hedging activity involving spot, futures, and options on Fed Funds. In particular, if options are delta hedged using futures, then options listing could be associated with an increase in the demand for liquidity in the futures market. This would certainly affect the futures rate.

Turning to the variance equation, the ARCH and GARCH parameters are positive and significant determinants of the conditional volatility of both the spot and the futures rates[9]. The error correction term has a positive and insignificant coefficient in the variance equation for the Fed Funds spot rate, suggesting that an increase in the deviation from a long run relationship has no effect on the spot market volatility. In contrast, ECM_{Fed} has a small but significant effect on the conditional volatility of the Fed Funds futures rate. The parameter is significant at the 1% confidence level. Finally, options listing dummy has a negative and significant slope coefficient in the variance equations for both the spot and the futures. The negative sign indicates that option

[9] Note that the sum of (α and β) is slightly over 1, indicating that the conditional variance may not be stationary over time, implying that a shock to the spot rate will cause its variance to drift infinitely.

listing is associated with a decrease in the volatility of the spot and the futures rates.

As indicated earlier, I chose the Eurodollar and the Libor markets as two popular interest markets with exchange traded options and futures contracts. For directional bets, trading, and risk management activities, these two markets are closely tied to the Fed Funds markets. As Kambhu (1998) points out, "for dynamic hedge adjustments, dealers are likely to use the most liquid instruments as hedging vehicles. In the U.S. dollar fixed-income markets, these instruments are Eurodollar futures, Treasury securities, and Treasury futures." Naturally, CBOT Fed Funds options listing might have some indirect effects on the mean and the volatility in these markets. In Table 2, the results indicate that the error correction term (ECM) is negative and significant in the mean equations for the Eurodollar markets, suggesting that a divergence between the spot and the futures markets is associated with a decrease in both markets. I find that the Fed Funds options listing dummy is positive and significant for the level of the Eurodollar spot and the futures rates. With respect to the conditional variance equations for the Eurodollar markets, the ECM is associated with a negative and significant coefficient in the conditional variance of the Eurodollar spot and a positive effect on the conditional variance of the Eurodollar futures rate. A negative effect of the Eurodollar ECM implies that an increase in the deviation between the Eurodollar spot and the futures is interpreted by the spot market participants as a resolution of uncertainty because these markets are expected to return to an equilibrium level. The ECM does not seem to affect the Eurodollar futures market volatility.

With regard to the effects of introduction of options on Fed Funds futures, the Eurodollar spot rate becomes more volatile while the volatility of the futures rate actually decreases. In the Libor markets, the ECM is positive for the Libor spot market rate and negative for the Libor futures rate. Both coefficients are significant at the 1% level. The options listing dummy has a positive effect on the level of the spot and futures on Libor. In terms of the conditional variance equations for these two rates, the results are as follows: the ECM is positively linked to the conditional volatility of both the spot and the futures rates. Finally, option listing does not affect the conditional variance of these two interest rates.

Table 2 also reports eleven interest rates that have been selected based upon the rationale that these rates are also closely tied to the Fed Funds markets. Some of these interest rates do not have futures contracts, therefore, the results are reported only for the spot rates. In addition, the univariate GARCH models are estimated without the market specific error correction term (ECM) in the mean and the volatility equations. The results indicate that option listing has a positive and significant coefficient for the level of the following rates: 1 month commercial paper rates (both non financial and financial AA rating), 1 month financial AA rated (asset backed) commercial paper rate, 1 month repo rate, and interest rate swap spreads of 1, 5, and 10 yr maturities. In terms of the size of the coefficient, the asset backed commercial paper has the largest value for the option listing dummy. In terms of the conditional variance of these markets, option listing has a positive and significant parameter for the following rates: Moody's AAA and BAA bond yields, non financial commercial paper rate, and 10yr US treasury rate. In contrast, option listing has a negative and significant effect on the conditional volatility of the asset backed commercial paper and the 1 month repo rate. With regard to robustness of these results, the results are quite powerful though the sum of ARCH and GARCH parameters exceeds 1 in 4 out of eleven instances. Further experiments with no drift constraint on the ARCH and GARCH are needed.

There are several shortcomings with estimating the univariate GARCH models to examine the effects of Fed Funds options introduction. First, these models assume that each market exists independent of its derivative market. While I have incorporated the market-specific ECM term as a way of tying a pair primary and derivative instruments (Fed Funds, the Eurodollar and the Libor), this alone is not sufficient. Second, univariate models are not full information maximum likelihood models because ideally they (both spot and futures equations) should be estimated jointly. Third, the univariate models fail to preserve important dynamic relationship between the markets, mainly the interaction between the conditional variances and covariances. Hence, it would not be possible to comment on any spillover between the markets without estimating a multivariate model. Fourth, these models fail to incorporate the joint distribution of the spot and futures which is implied by the fundamental pricing relationship. Fifth, the analysis also fails to examine whether spot market reaction to options listing differs from the futures market reaction while allowing each market to express its own reaction, but not in isolation[10]. In other words, the spot market reaction to options introduction will take into consideration the response of the futures market, and vice versa. Finally, the univariate models do not account for the correlation between the markets because of missing interaction between the volatilities.

In light of these limitations, I estimate the following multivariate GARCH error correction model that assumes that the second moments of $dlnS_t$ (changes in the natural log of Fed Funds spot rate) and $dlnF_t$ (changes in the natural log of Fed Funds futures rate) can be parameterized by a bivariate GARCH(1,1) model[11]. The model is:

(1)
$$\Delta \ln S_t = \alpha_0 + \alpha_1 ECM_{t-1} + \alpha_2 Listing + \varepsilon_{st}$$
$$\Delta \ln F_t = \beta_0 + \beta_1 ECM_{t-1} + \beta_2 Listing + \varepsilon_{ft}$$

(2)
$$\begin{bmatrix} \varepsilon_s \\ \varepsilon_f \end{bmatrix} | \psi_{t-1} \sim N(0, H_t)$$

[10] One can also infer the impacts on futures markets by examining the impact on the markets for the underlying assets since the two are related. However, the effects may differ since the "marked to market" feature and expiration of futures contracts may cause the underlying stochastic process for futures prices to differ from that for the underlying asset.

[11] For a similar application of this model, see Kroner and Sultan (1993).

(3)

$$H_t = \begin{bmatrix} h_{st} \\ h_{sft} \\ h_{ft} \end{bmatrix} = \begin{bmatrix} \tau_s \\ \tau_{sf} \\ \tau_f \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \varepsilon^2_{st-1} \\ \varepsilon_{st-1}\varepsilon_{ft-1} \\ \varepsilon^2_{ft-1} \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} h_{st-1} \\ h_{sft-1} \\ h_{ft-1} \end{bmatrix} + \begin{bmatrix} \theta_s \\ \theta_{sf} \\ \theta_f \end{bmatrix} ECM_{t-1} + \begin{bmatrix} \lambda_s \\ \lambda_{sf} \\ \lambda_f \end{bmatrix} Listing$$

where Ψ_{t-1} is the information set at time *t-1*. In this model, equation (1) describes the mean equations, equation (2) specifies the joint distribution of the error terms in the mean equations, and equation (3) defines the full functional form of the variance and covariance of the error terms. Note that convergence of the above model is often problematic because of 21 parameters. The diagonal specification allows one to concentrate only on the diagonal elements of the ARCH and GARCH matrices though convergence is still not guaranteed. The diagonal version of the above model is:

(4)

$$dln\,S_t = \alpha_0 + \alpha_1 ECM_{t-1} + \alpha_2 Listing + \varepsilon_{st}$$
$$dln\,F_t = \beta_0 + \beta_1 ECM_{t-1} + \beta_2 Listing + \varepsilon_{ft}$$

(5)

$$H_t = \begin{bmatrix} h_{st} \\ h_{sft} \\ h_{ft} \end{bmatrix} = \begin{bmatrix} \tau_s \\ \tau_{sf} \\ \tau_f \end{bmatrix} + \begin{bmatrix} a_{11} & 0 & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{bmatrix} \begin{bmatrix} \varepsilon^2_{st-1} \\ \varepsilon_{st-1}\varepsilon_{ft-1} \\ \varepsilon^2_{ft-1} \end{bmatrix} + \begin{bmatrix} b_{11} & 0 & 0 \\ 0 & b_{22} & 0 \\ 0 & 0 & b_{33} \end{bmatrix} \begin{bmatrix} h_{st-1} \\ h_{sft-1} \\ h_{ft-1} \end{bmatrix} + \begin{bmatrix} \theta_s \\ \theta_{sf} \\ \theta_f \end{bmatrix} ECM_{t-1} + \begin{bmatrix} \lambda_s \\ \lambda_{sf} \\ \lambda_f \end{bmatrix} Listing$$

The mean equations (equations 4) use the first difference in the natural logarithms of daily Fed Funds spot rates and futures rates. The first independent variable ECM (lnF_{t-1}-lnS_{t-1}) is the error correction term which accounts for cointegration between the spot and futures rates. This presumes (see Brenner and Kroner (1993)) that the cointegrating vector is (1,-1). The specific form of this cointegrating vector follows from the notion that the spot and the futures markets are tightly linked through monetary policy variables as well as institutional requirements. In the stock market, the stock index and futures on the stock index would be related to one another through index arbitrage (see Stoll and Whaley (1990)). Because the spot and futures prices are cointegrated, the omission of the ECM term would result in a model misspecification. The options listing dummy is included in the mean and variance equations to examine if options listing is associated with any change in the interest rates and their volatilities. Listing dummy is set equal to 1 since options on futures were introduced, and 0 otherwise.

In the variance equation (5), the first terms on the right hand side (τs) are the constant terms, the second terms represent the impact of the lagged squared residuals (ARCH coefficients), and the third terms represent the conditional variance-covariance of spot and futures rate changes (GARCH coefficients). Finally, θs are the coefficients of the error correction term (ECM) and λs are coefficients for futures options listing dummy. The location of each parameter is designated with a subscript. For example, λ_{sf} captures the effects of options listing on the time varying covariance between the spot and futures markets, while λ_f documents the effects on the volatility of the Fed Funds futures. The models are estimated using the BHHH method with robust standard errors. As Bollerslev and Wooldridge (1992) note, statistical inferences based on the student-t when the residuals are non-normal may be misleading because the standard errors are biased. Estimating robust standard errors allows one to avoid both heteroskedasticity and serial correlation in the residuals.

There are several additional reasons for proposing a bivariate system. First, one of the critical roles of the futures markets is that it provides relevant information about the underlying commodities. This price discovery function suggests that as the futures contracts approach maturity, the rate of information acquisition increases (the Samuelson Effect). Therefore, futures prices should be more volatile than the spot market when contracts come closer to maturity. This suggests the use of a bivariate system since I would expect the information effect to be larger in the futures market as compared to the spot market. In addition, I would also expect the futures market to adjust faster to information arrival as compared to the spot. Consequently, the spot market would display only a residual (or delayed) impact of a particular set of information. However, estimating a single equation model would not allow one to incorporate the differential impact of information in the spot and futures markets. Second, the GARCH is suited for modeling high-frequency time series data with clusters of volatility as primary markets interact with information flow. Previous studies have failed to incorporate this non-linear distribution of underlying markets in examining the impact of options listings.

In Table 3, the results from estimating multivariate GARCH models are reported as follows: Column A reports the results for the Fed Funds spot and futures rates, Column B reports the results for the 3 month Eurodollar spot and futures rates, while Column C reports the estimates for the 1 month Libor spot and futures rates. In the Fed Funds markets (Column A), the error correction term is significantly negative in both equations. The variable has a larger coefficient in the spot market and the negative sign indicates that deviation from a fundamental relationship forces both markets to simultaneously decline. Options-listing has a negative effect on the conditional mean for the Fed Funds spot. In contrast, the effect on the conditional mean for the futures is positive. Note that these results are quite similar to the single equation models presented in Table 2. In the variance-covariance matrix, the ECM is only significant in the conditional variance for the Fed Funds futures market. While the magnitude of the effects is small, the statistical significance is quite strong. A negative sign for ECM indicates that when the spot and the futures markets deviate from one another, there is less uncertainty in the market because the markets are expected to return to an equilibrium level. In other words, there is a resolution of uncertainty in the market. The introduction of options is associated with a negative effect on the volatility of both markets. In addition, the conditional covariance term is also negatively related to the option introduction dummy variable. These results are strikingly similar to the ones reported in Table 2.

Overall, an introduction of options on the Fed Funds futures leads to a decrease in the interest rates volatility and the covariance between the markets. This is of major significance to the paper as it reinforces previous results that derivatives do not make the underlying markets more volatile. Options introduction leads to a more informed participation in the market and helps in an efficient allocation of risk among market participants. As risk allocation and price discovery improves, the markets become more stable (Grossman, 1988).

For the Eurodollar markets, the results are as follows: the ECM variable has a negative coefficient in both the spot and the futures markets. Option listing variable has a positive effect on the conditional volatility of both markets. Again, the results are quite similar to the ones reported in Table 2. In the covariance matrix, ECM has a negative effect on the conditional covariance between the spot and the futures rates. Option listing has a positive effect on the volatility of the Eurodollar spot rate and the covariance between the Eurodollar spot and futures rates. Note that the parameters a12 and b12 parameters (which are capturing covariance effects) are negative, suggesting that these results should be interpreted with caution.

Finally, the Libor results are reported in Column C. The variable ECM has a positive signed coefficient in the conditional mean equation for the Libor spot rate while the effect for the conditional mean of the Libor futures is negative. In addition, only the Libor spot rate responds positively to the introduction of option on the Fed Funds. These results are somewhat different than the results reported in table 2. In the covariance matrix, the ECM has a negative parameter for both the conditional covariance between the Libor spot and the futures rate, and the variance of the Libor futures rate. Similar to the previous results in Table 2, option introduction did not affect the conditional variance of the Libor spot and futures rates.

IV. Conclusions

This paper examines the effects of option introductions on the volatility of popular interest rates including the Fed Funds spot and futures rates. This study extends the literature in several ways. In addition to univariate GARCH models, this study estimates multivariate GARCH error correction models to examine the effects of options introduction. The multivariate GARCH models assume the spot or the futures market does not exist in a vacuum without any link to one another. Econometrically, this is achieved by introducing the error correction term (ECM) as a way of tying a pair of markets where the spot and the futures are fundamentally related to one another. The multivariate GARCH models are full information maximum likelihood models and are estimated jointly. In addition, the multivariate GARCH model preserves important dynamic relationship between the markets, mainly the interaction between the conditional variances and covariances. Next, the multivariate GARCH error correction model allows one to examine whether spot market reaction to options listing differs from the futures market reaction; while allowing each market to express its own reaction, but not in isolation[12]. Finally, the GARCH model allows one to examine the impact of various exogenous variables simultaneously on the volatility of the spot and futures rates and to conduct several specification tests.

Critical findings of this study are that an introduction of the options on Fed Funds futures is associated with a decrease in the level of the Fed Funds spot and futures. The results also indicate that options introduction is associated with a decrease in the conditional volatility of the Fed Funds spot, Fed

[12] One can also infer the impacts on futures markets by examining the impact on the markets for the underlying assets since the two are related. However, the effects may differ since the "marked to market" feature and expiration of futures contracts may cause the underlying stochastic process for futures prices to differ from that for the underlying asset.

Funds futures and their covariance. This alone suggests that options on Fed Funds futures stabilize the Fed Funds markets. With respect to the related interest rate markets, the results are as follows. I find that the level of the Eurodollar spot and futures increased following the listing of options on the Fed Funds futures. In addition, the volatility of the both the Eurodollar spot and its covariance with the Eurodollar futures have increased after options listing. For the Libor market, the results are weak. I find that the option introduction is associated with an increase in the Libor spot rate while there was no effect on the conditional volatility of the Libor spot and futures rates. Overall, these results suggest that derivatives products do not cause the underlying primary markets to become unstable by increasing their volatility though their effects on related markets are not uniform.

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Table 1

Diagnostic Statistics
Panel A: Sample Statistics on Raw Data

Variable	Mean	Std. Error	Skewness	Kurtosis	Jarque-Bera	Ljung-Box	TR^2
Δln FF Spot	-.012	5.059	0.683	24.785	122001.650	615.0856	1032.845
Δln FF Futures	-.010	1.073	0.938	75.914	1141780.909	324.231	271.643
Δln Euro$	-.004	1.079	-0.945	24.531	127104.935	135.302	108.744
Δln Euro$ Fut	-.006	1.266	0.816	27.915	164170.276	117.660	97.943
Δln Libor	-.009	1.090	1.409	141.716	3657498.485	179.082	162.795
Δln Libor Fut	-.010	1.350	0.862	66.911	815577.044	91.957	89.531

Panel B: ARIMA Regression Results

	Intercept	9/11	Target	Monday	Tuesday	Wednesday	Thursday
Δln FF Spot	-1.022	-5.055	0.872	1.791	0.01	2.064	1.279
	(-6.640)***	(-2.280) ***	(36.020) ***	(7.760) ***	(0.040) ***	(8.280) ***	(5.230) ***
Δln FF Fut	-0.048	-6.380	0.159	0.123	0.049	0.037	-.003
	(-1.340)	(-6.230)***	(13.480)***	(2.740)***	(1.130)	(0.830)	(-0.080)
Δln Euro$	-0.033	-6.798	0.057	-0.020	0.154	-0.025	0.046
	(-0.920)	(-6.360)***	(4.670)***	(-0.420)	(3.330)***	(-0.540)	(0.990)
Δln Euro$ Fut	-0.065	-7.061	0.135	0.176	0.024	0.100	0.1020
	(-1.630)	(-5.650)***	(9.380)***	(3.290)***	(0.450)	(1.860)**	(0.390)
Δln Libor	0.041	-8.343	0.018	-0.086	-0.009	-0.077	-.069
	(1.100)	(-7.870)***	(1.450)	(-1.780)*	(-0.210)	(-1.620)	(-1.460)
Δln Libor Fut	-0.729	-8.609	0.145	0.213	0.031	0.066	0.026
	(-1.590)	(-4.980)***	(9.270)***	(3.400)***	(0.490)	(1.020)	(0.420)

Panel C: Sample Statistics on Fitted Values

Variable	Mean	Std. Error	Skewness	Kurtosis	Jarque-Bera	Ljung-Box	TR^2
Δln FF Spot	-.012	2.959	0.468	42.618	359812.335	854.550	825.036
Δln FF Futures	-.010	0.340	-1.417	70.751	992748.851	1531.003	746.688
Δln Euro$	-.004	0.204	-9.776	349.989	25798693.291	2726.441	945.973
Δln Euro$ Fut	-.0051	.267	-3.973	118.657	2969385.263	1055.008	549.245
Δln Libor	-.009	0.244	-12.763	475.309	41245369.133	1290.877	823.547
Δln Libor Fut	-.010	0.293	-3.482	87.612	1406167.614	399.274	363.398

Note: Fitted values are obtained from ARIMA regressions reported in Panel B. The ARIMA regressions were estimated using the maximum likelihood procedure with 24 lags on AR terms. In some cases, there were residual autocorrelation even at 23rd lag of the AR term. In other cases, the ARIMA model, though overfitting the data, provides a reasonable way to take into account some of the stylized effects on these interest rates.

Panel D: Test for Cointegration

Variable	Dickey-Fuller Test Statistic	Cointegration Test Statistic
ln FF Spot	-0.410	-9.911
ln FF Futures	-0.326	
ln Euro$	-0.313	-5.813
ln Euro$ Fut	-0.508	
ln Libor	-1.142	-10.059
ln Libor Fut	-1.178	

Table 2

Univariate GARCH Regressions

In this table, I report univariate GARCH models to examine the effects of CBOT Fed Funds futures options listing. For the fitted values of Fed Funds spot and futures, the variable ECM is the error correction term between the Fed Funds spot and futures rates. In the case of the 3m Eurodollar spot and futures, the variable ECM represents the error correction term between the 3m Eurodollar spot and futures rates. A similar explanation holds for the 1m Libor spot and futures rates. For the remaining interest rates and bond yields, the term ECM is set to zero because there is only one primary market for these products and the futures contracts do not exist for them. t-statistics (in parenthesis) are based on robust standard errors. Significance levels are denoted as follows: *** (1%), ** (5%)

	Mean Equation			**Variance Equation**				
Variable	**Intercept**	**ECM**	**Option**	**Intercept**	**ARCH**	**GARCH**	**ECM**	**Option**
<u>Fed Funds</u>								
Δln FF Spot	-.002	-.411	-.351	.121	.235	.756	.001	-.041
	(-.065)	(-111.988)***	(-7.237)****	(7.257)****	(16.063)***	(71.257)***	(0.377)	(-2.121)**
Δln FF Fut	-.007	-.010	.014	4.2e-04	.167	.889	-7.39e-05	-4.64e-04
	(-3.984)***	(-57.329)***	(4.139)***	(15.606)***	(45.536)***	(551.892)***	(-8.137)***	(-8.807)***
<u>Eurodollar</u>								
Δln E$ Spot	-9.7e-03	-3.68e-03	.027	7.57e-04	.178	.831	-1.9e-05	3.2e-05
	(-3.905)***	(8.937)***	(5.555)***	(10.498)***	(103.795)***	(208.069)***	(-2.480)**	(4.435)***
Δln E$ Fut	-.023	-8.6e-03	.022	1.4e-04	.058	.951	1.7e-06	-1.3e-04
	(-7.806)***	(-17.491)***	(3.936)***	(14.674)***	(67.892)***	(1331.457)***	(.492)	(-4.891)***
<u>Libor</u>								
Libor Spot	-7.7e-04	2.8e-04	.014	1.0e-04	.568	.666	2.0e-06	-7.8e-05
	(-.579)	(14.463)***	(6.523)***	(2.505)**	(47.762)***	(134.694)***	(.215)	(-1.318)
Libor Fut	-9.5e-03	-.011	.013	8.6e-05	.141	.903	8.7e-05	-1.2e-05
	(-4.364)***	(-25.982)***	(2.677)***	(2.171)**	(47.931)***	(548.535)***	(9.216)***	(-.158)

Table 2 (contd.)
Univariate GARCH Regressions

In this table, I report univariate GARCH models to examine the effects of CBOT Fed Funds futures options listing. For the fitted values of Fed Funds spot and futures, the variable ECM is the error correction term between the Fed Funds spot and futures rates. In the case of the 3m Eurodollar spot and futures, the variable ECM represents the error correction term between the 3m Eurodollar spot and futures rates. A similar explanation holds for the 1m Libor spot and futures rates. For the remaining interest rates and bond yields, the term ECM is set to zero because there is only one primary market for these products and the futures contracts do not exist for them. t-statistics (in parenthesis) are based on robust standard errors. Significance levels are denoted as follows: *** (1**), **

	Mean Equation			**Variance Equation**				
Variable	**Intercept**	**ECM**	**Option**	**Intercept**	**ARCH**	**GARCH**	**ECM**	**Option**
AAA	-.010		-.00001	.000001	.039	.957		.00002
	(-13.748)***		(-0.073)	(2.862)***	(8.969)***	(194.351)***		(2.103)**
BAA	-.0009		-.00003	.00001	.039	.955		.00002
	(-13.031)***		(-.152)	(3.075)***	(8.662)***	(175.374)***		(2.181)**
A2P2	-.003		.006	.002	.185	.849		-.001
	(-.403)		(.482)	(5.752)***	(24.037)***	(150.132)***		(-1.410)
Cpnfin	.007		.015	.0001	.411	.783		.0003
	(4.132)***		(2.500)**	(5.425)***	(101.199)***	(476.442)***		(2.419)**
CPAAfin	.023		.014	.003	.843	.517		.0001
	(5.967)***		(2.480)**	(5.365)***	(27.008)***	(29.399)***		(.192)
CPasset backed	-.047		.079	.011	.628	.503		-.009
	(-4.193)***		(6.478)***	(15.332)***	(32.364)***	(32.365)***		(-13.805)***
1m Repo	-.004		.035	.004	.150	.825		-.002
	(-.338)		(2.862)***	(5.000)***	(9.493)***	(56.255)***		(-3.795)***
Swap1yr	-.002		.019	.0003	.118	.889		.00006
	(-.591)		(2.480)**	(2.570)**	(29.862)***	(147.463)***		(.388)
Swap5yr	-.013		.016	.0003	.078	.912		.00003
	(-6.091)***		(3.137)***	(6.700)***	(42.026)***	(241.186)***		(.428)
Swap10yr	-.013		.009	.0002	.049	.912		.00006
	(-7.542)***		(2.046)**	(5.742)***	(42.026)***	(241.186)***		(1.476)
UST10yr	-.011		.002	.00009	.037	.948		.00004
	(-9.452)***		(.655)	(3.972)***	(8.308)***	(143.312)***		(2.050)**

Table 3
Multivariate GARCH Error Correction Model

	Fed Funds Model	Eurodollar Model	Libor Model
α_0	.0002	-.0164	-.0001
	(.823)	(-5.440)***	(-1.443)
β_0	-.0007	-.028	-.012
	(-3.553)***	(-8.679)***	(-5.703)***
$\alpha_1(ECM_{t-1})$	-.423	-.0005	.0004
	(-102.667)***	(-10.934)***	(16.603)***
$\beta_1(ECM_{t-1})$	-.011	-.0009	-.014
	(-40.225)***	(-17.745)***	(-33.025)***)
α_2 (Option)	-.344	.039	.011
	(-6.543)***	(6.313)***	(5.596)***
β_2(Option)	.014	.035	.0006
	(3.802)***	(4.731)***	(1.480)
τ_s	.140	.002	.00002
	(7.617)***	(12.348)***	(.578)
τ_{sf}	.0006	.008	-.0005
	(2.610)**	(17.375)***	(-10.911)***
τ_f	.00005	.00004	.00001
	(15.356)***	(22.598)***	(.075)
a_{11}	.241	.182	.54
	(15.199)***	(38.922)***	(45.730)***
a_{12}	.056	-.089	-.042
	(4.842)***	(-28.183)***	(-6.550)***
a_{22}	.165	.041	.134
	(42.702)***	(22.630)***	(36.811)***
b_{11}	.743	.766	.687
	(63.083)***	(75.373)***	(136.624)***
b_{12}	.576	-.675	-.898
	(4.817)***	(-16.764)***	(-95.606)***
b_{22}	.889	.954	.909
	(519.915)***	(605.187)***	(487.121)***
$\theta_s(ECM_{t-1})$	.00006	-.00001	.000006
	(.215)	(-.098)	(.739)
$\theta_{sf}(ECM_{t-1})$	-.00001	-.0002	-.00007
	(-.582)	(-2.071)**	(-2.245)**
$\theta_f(ECM_{t-1})$	-.000008	.00001	.00007
	(-8.642)***	(.537)	(7.437)***
ω_s(Option)	-.045	.00006	-.000003
	(-2.094)**	(3.484)***	(-.504)***
ω_{sf}(Option)	-.00005	.0004	.00004
	(-1.908)*	(5.310)***	(.643)
ω_f(Option)	-.00005	-.00001	-.00001
	(-8.817)***	(-.270)	(-.185)

Table 3 (contd.)

Multivariate GARCH Error Correction Model

In this table, multivariate GARCH results are reported for three popular interest rates spot and their corresponding futures rates. The model is of the following kind:

$$dln\,S_t = \alpha_0 + \alpha_1 ECM_{t-1} + \alpha_2 Option + \varepsilon_{st}$$
$$dln\,F_t = \beta_0 + \beta_1 ECM_{t-1} + \beta_2 Option + \varepsilon_{ft}$$

$$H_t = \begin{bmatrix} h_{st} \\ h_{sft} \\ h_{ft} \end{bmatrix} = \begin{bmatrix} \tau_s \\ \tau_{sf} \\ \tau_f \end{bmatrix} + \begin{bmatrix} a_{11} & 0 & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{bmatrix} \begin{bmatrix} \varepsilon^2_{st-1} \\ \varepsilon_{st-1}\varepsilon_{ft-1} \\ \varepsilon^2_{ft-1} \end{bmatrix} + \begin{bmatrix} b_{11} & 0 & 0 \\ 0 & b_{22} & 0 \\ 0 & 0 & b_{33} \end{bmatrix} \begin{bmatrix} h_{st-1} \\ h_{sft-1} \\ h_{ft-1} \end{bmatrix} + \begin{bmatrix} \theta_s \\ \theta_{sf} \\ \theta_f \end{bmatrix} ECM_{t-1} + \begin{bmatrix} \lambda_s \\ \lambda_{sf} \\ \lambda_f \end{bmatrix} Option$$

In the mean equations, the dependent variables are 100*dlnS_t and 100*dlnF_t. Among the independent variables, ECM (=lnS_{t-1}-lnF_{t-1}) is the error correction term which accounts for cointegration between the spot and futures rates. Each model has its own error correction term. The model also includes Option (the listing dummy) which takes a value of 0 before options on Fed Funds futures started trading at CBOT and 1 otherwise. Position of the independent variables in the variance-covariance matrix is indicated by the subscripts: s (spot), f (futures), and sf (covariance). This model assumes that the off-diagonal elements of the A and B matrices are zero, which is convenient for convergence of the model. t-statistics (in parentheses) are based on robust standard errors. Significance levels are denoted as follows: *** (1%), **(5%), and * (1%)

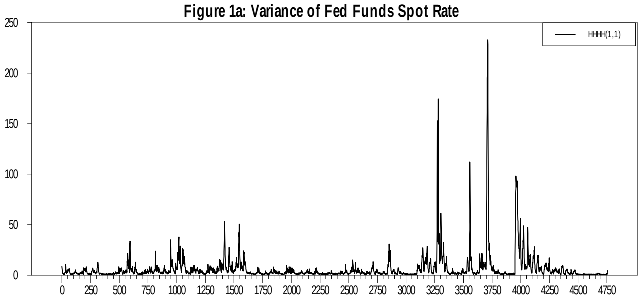

Figure 1a: Variance of Fed Funds Spot Rate

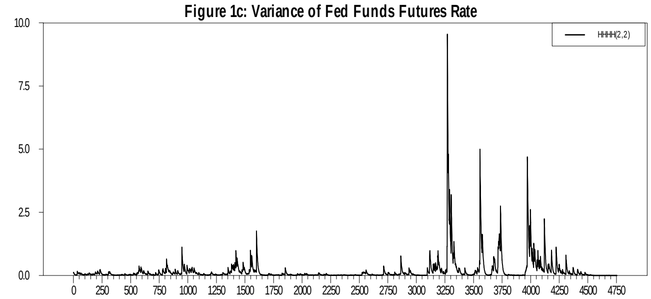

Figure 1c: Variance of Fed Funds Futures Rate

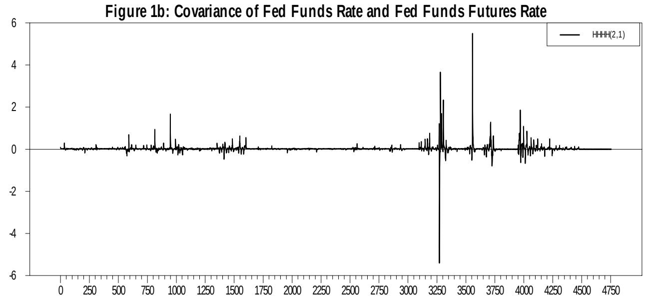

Figure 1b: Covariance of Fed Funds Rate and Fed Funds Futures Rate

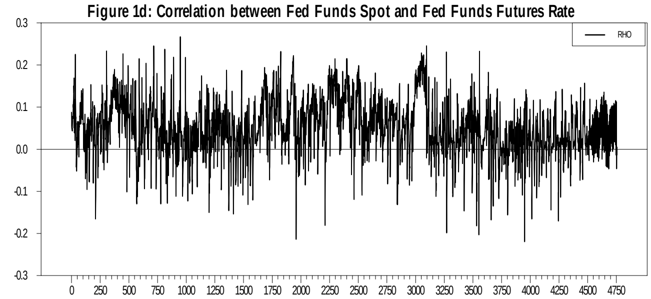

Figure 1d: Correlation between Fed Funds Spot and Fed Funds Futures Rate

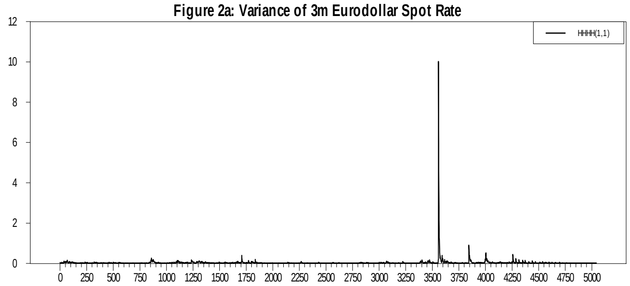

Figure 2a: Variance of 3m Eurodollar Spot Rate

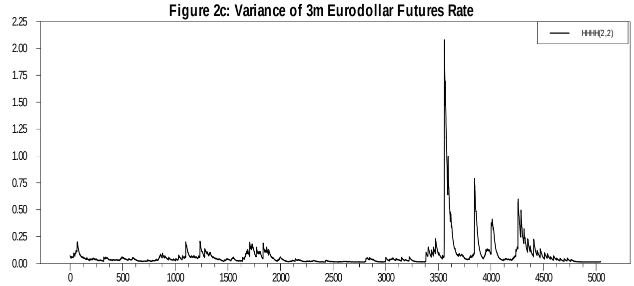

Figure 2c: Variance of 3m Eurodollar Futures Rate

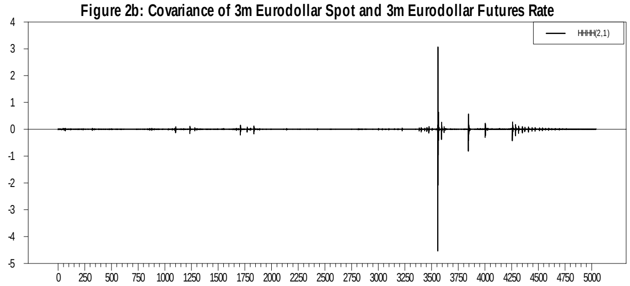

Figure 2b: Covariance of 3m Eurodollar Spot and 3m Eurodollar Futures Rate

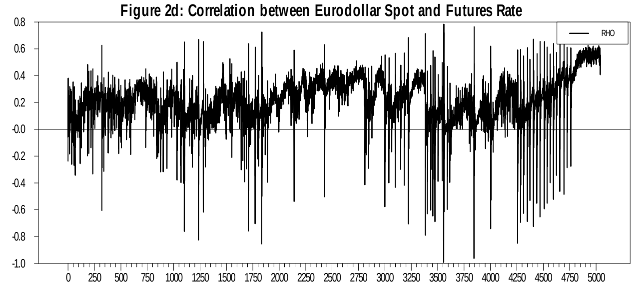

Figure 2d: Correlation between Eurodollar Spot and Futures Rate

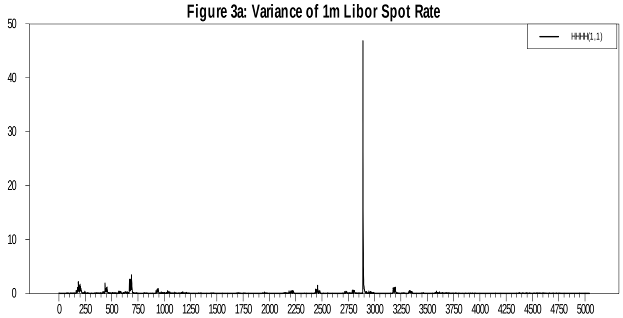

Figure 3a: Variance of 1m Libor Spot Rate

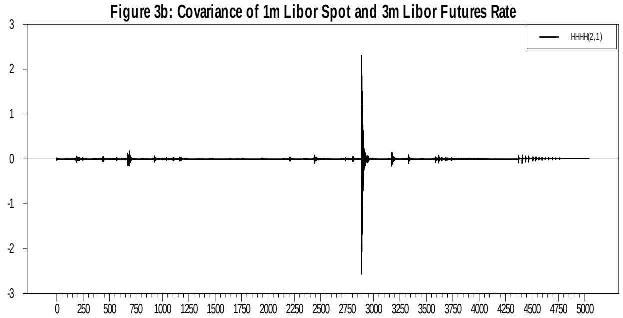

Figure 3b: Covariance of 1m Libor Spot and 3m Libor Futures Rate

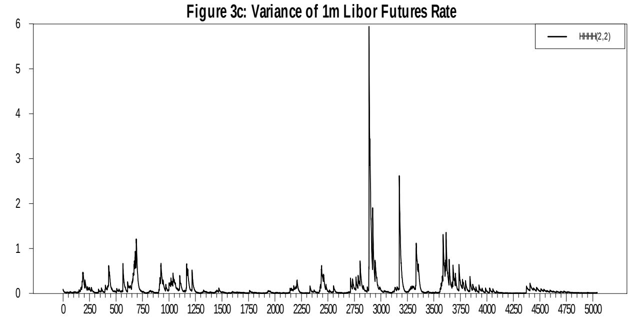

Figure 3c: Variance of 1m Libor Futures Rate

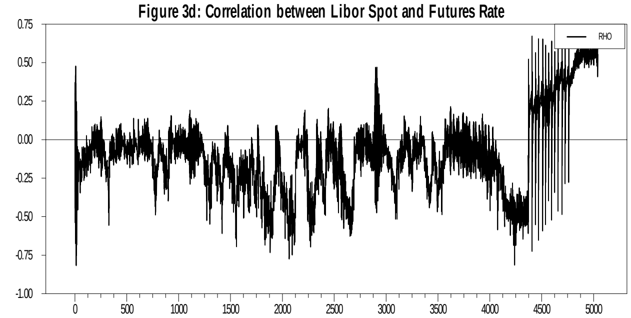

Figure 3d: Correlation between Libor Spot and Futures Rate