The Valuation of Equity Futures on the Tokyo Stock Exchange 1920-1923

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Abstract

The futures price of an asset should depend on the spot price of that asset, the interest rate, any cashflows during the contract term, the convenience yield, and storage costs. Despite many tests of the spot-future relation for commodities in historical periods, there have been no tests of this relation for equities as early as the 1920s. We price single-stock equity futures on the Tokyo Stock Exchange between 1920 and 1923 and find that mispricing is considerably worse than in contemporary U.S. markets, after adjusting for (unavoidable) asynchronous data issues.

The extent to which derivative pricing models describe financial markets has been the topic of much recent research, focusing on whether market participants have correctly priced derivatives prior to the academic development of formal pricing formulae. Murphy (2009) shows that 17$^{\text{th}}$ century London priced equity options quite accurately, while Moore and Juh (2006) present similar evidence for South African options traders in the early 20$^{\text{th}}$ century. Both results are striking, since the Black-Scholes-Merton formula was not developed until the 1970s (see Black and Scholes (1973) and Merton (1973)). In contrast, the examination of futures contract pricing has been less conclusive, in spite of these markets being older and more established than options markets. Wakita (2001) and Bell, Brooks and Dryburgh (2007) present evidence on the Dojima rice market and the medieval English wool market, respectively. However, their results are difficult to interpret given the difficulty of measuring the convenience yield and storage costs for commodities. This is an inevitable shortcoming, since although derivative securities have existed for thousands of years, they were primarily traded off-exchange and mainly written on commodity contracts prior to the 20$^{\text{th}}$ century.

We study the pricing efficiency of single-stock equity futures on the Tokyo Stock Exchange (TSE) from 1920 to 1923. Although the futures we study are not the first financial derivatives to have been traded, we have not found any studies that test the efficiency of futures markets for financial products using earlier data. The Japanese equity market during this era was mainly a futures market; spot trades did exist, but the equity of major companies traded primarily via 1-month, 2-month, and 3-month futures contracts (see Hamao et al (2009)). Given a long history of futures trading in Japan and a large liquid market, an examination of pricing on the TSE will allow us to assess whether futures markets had in fact eliminated arbitrage opportunities, even though academics were still debating the issue of the spot-forward relationship. We test no-arbitrage futures pricing using daily data on 29 stocks traded on the TSE. Although Tokyo was not the earliest market to regularly trade financial futures (which was Amsterdam in the 17th century, according to Weber (2009) p. 440), it is the first market with standardized terms for trading a wide range of financial futures for which reliable price data exist.

Futures trading in Japan began around 1730, with the chartering of the Dojima rice market by the Tokugawa shogunate (see Takatsuki (2008) and Hersent and Simon (1989)). Trade was done in claims on rice, *kome kitte*, each of which was equivalent to about 1500kg of rice. There was both a spot market and a market for future delivery. There was a clearing house for the futures market, and buying and selling orders were netted out on a daily basis. Schaede (1989) argues that Dojima was the first market in the world with characteristics we currently associate with futures markets: standardized contracts, a clearing house, marking to market, and cash payments to settle contracts. Miyamoto (1977) has shown a strong correlation between spot and futures prices for rice between 1731 and 1859. Hamori et al (2001) argue that the Dojima market was efficient during the period 1763-1780, but less efficient in a later period, 1851-64.

Following the Meiji Restoration of 1868, the Tokyo Stock Exchange (TSE) was founded in 1878. Given the background of more than a century of futures trading of rice it was natural that when stock markets were introduced in Japan, futures trading was preserved. The Stock Exchange Act of 1878 allowed both spot (*genba torihiki*) and futures (*teiki torihiki*) transactions (see Hamao et al (2009)). Delivery dates for the Tokugawa-era rice markets had been non-standardized. For example, traders in the 'spring market' for rice could not write contracts for rice delivery past April 28 of that year (see Wakita (2001) p. 538). In contrast, the Stock Exchange Act specified standardized delivery dates for single-stock equity futures, extending out to a maximum of three months.

To place the pricing efficiency of early 20th century Japanese investors in perspective, we compare the mispricing of TSE futures with contemporary U.S. single-stock futures available from OneChicago between 2008 and 2010. This will aid us to evaluate how well Japanese investors were performing in comparison with investors in today's largest financial marketplace. We calculate mispricing of approximately 1.7% in Japan, the same as that observed in the modern U.S. However, both sets of daily data are unfortunately asynchronous, and part of the mispricing we find can be explained by time mismatched prices. The asynchronous aspect of the data completely explains the observed U.S. mispricing and greatly reduces the Japanese mispricing.

I History of Futures and their Pricing

A History of Futures Markets

In the past the primary use of derivatives has been to hedge risk for producers and consumers of physical, often agricultural, goods. For example, the Chicago Board of Trade was set up in 1848 to facilitate trading in grain, beef, pork, and lumber (see Markham (1987)).

Derivatives have existed alongside the market economy over the course of history. Van de Mierop (2005) reports a contract in Mesopotamia in the 19th century B.C. for the future delivery of wood, written on clay tablets, and Swan (2000) reports details of barley short-selling in the 17th century. Hou (1997) reports forward contracts on Chinese rice as early as 2000 BC. Derivative contracts have also been found in classical Egyptian and Roman records for the delivery of trade goods (see Weber (2009)). Weber reports that the innovation of settling futures contracts by cash settlement, rather than taking delivery of the goods, was introduced in Antwerp during the Renaissance. He finds that it was soon after the formation of modern joint-stock companies in Amsterdam in the 17th century that futures contracts on equity securities were written: 'shares sold not only for cash but on term. This was not an innovation for Amsterdam, since term sales had been the custom for sales in wheat and herring' (van Dillen (1935, pp. 53, 58) as reported by Weber (2009)). French law permitted derivative trading on securities listed on the Paris Bourse in the 1850s (see Proudhon (1857) p. 81) as long as the time to delivery did not exceed 2 months (1 month for railway shares). Although many securities quoted on the Paris Bourse were traded both for spot and future delivery, the spot market was substantially more liquid. In addition, almost all future securities' delivery dates were the end of the current month, making the distinction between spot and futures prices (ie. the time value of money) a secondary concern for investors.

B The Tokyo Stock Exchange

The Tokyo Stock Exchange has been the most important stock exchange in Japan since its founding, although it faced strong competition from the Osaka Stock Exchange in the pre-World War Two period. Between 1920 and 1923 the TSE received about 40% of all Japanese exchanges' revenues, which were mainly derived from commission on trading, compared to around 30% for Osaka (regional exchanges accounted for the remainder).

There were between 600 and 800 equity securities traded on the TSE spot market in the early 1920s. A subset of around 200 of the larger and more liquid firms were traded on the 'long-term' futures market. Futures contracts could be resold as many times as desired during the duration of the contract. At expiry the difference between the futures price at the beginning of the contract and the spot price at the end of the contract was settled in cash, ownership of the shares was not transferred. TSE futures contracts came in three durations: one-month, two-month, and three-month. One-month futures expired on the last trading day of the month, and similarly for two- and three-month contracts.[1] There were no margin accounts used for these contracts. Although margin accounts are a standard feature of futures contracts we refer to these contracts as 'futures' for the remainder of the paper. Given that they had standardized expiration dates, and were exchange traded, they can not be properly termed forward contracts either.

Futures had been traded in a basically unchanged form since the founding of the exchange. In 1924 (just after our period of study) three-month futures contracts were removed and 'short-term' futures, in which delivery had to occur within 24 hours or a penalty paid, were introduced. A small subset of those firms quoted on the long-term futures market began to be traded on the short-term futures market (as well as on the long-term and spot market). The spot market appears to have comprised many small firms and to have been very illiquid. Hamao et al (2009) p. 17 state that: 'it seems safe to conclude that the TSE did not have explicit listing criteria for the spot market.' Most positions taken on large firms occured via the futures market. The Ministry of Agriculture and Commerce imposed the following requirements on the long-term market in 1914: (i) the firm must be at least 2 years old; (ii)

[1] See Hamao et al (2009) p. 8.

the total paid-in nominal value must be at least one million yen (approximately $0.5 million); and (iii) if a firm already had shares traded on the futures market, subsequent issues needed to have a paid-in nominal value of at least 500,000 yen.[2]

Even if a firm met all of these requirements the TSE could refuse listing status. In May 1921 the TSE tightened listing requirements further. A firm's total nominal capital had to be at least three million yen, of which one million had already been paid up (many firms issued partly paid shares), and there had to be at least 60,000 shares issued.[3]

C Theory of Futures Pricing

The relation between spot and futures prices, for commodities, appears to have been somewhat understood by market participants in the early 20th century. For example Boyle (1921, p. 61), in a treatise on Chicago Board of Trade grain futures, states that: 'the natural position of futures, in months under old-crop influences (i.e. just before harvest time), is of course above cash by the amount of the carrying charges. The "carrying charge" includes the storage charge in the terminal elevator, the insurance on the grain, and the interest on the money invested.' On the other hand, Keynes (1930) p. 143, in discussing commodity forwards, states that: 'if supply and demand are balanced, the spot price must exceed the forward price by the amount which the producer is ready to sacrifice in order to "hedge" himself', which suggests that futures prices require equilibrium (i.e. preference specific) pricing as opposed to no-arbitrage pricing. Keynes goes on to add that, surplus stocks 'cause the forward price to rise *above* the spot price …and this contango must be equal to the cost of the warehouse, depreciation and interest charges of carrying the stocks', suggesting the beginnings of a no-arbitrage spot-forward relationship. The correct pricing of futures contracts was hotly debated during 1939-40. Kaldor (1939, 1940) argues (correctly) for the presence of arbitrageurs setting a forward price based on carry costs, leading to positive or negative expected returns depending on the relative size of risk premia relative to the carry cost. In contrast, Dow (1940*a*, 1940*b*) and Hawtrey (1940) argue that divergences of opin-

[2]See Hamao et al (2009) p. 15-16.
[3]See Hamao et al (2009) p. 16-17.

ion among speculators and hedgers may lead to different equilibrium forward prices, with Dow (1940*a*) arguing that speculators may choose to hold unhedged positions when their risk-premia are less than carry costs. Arbitrage pricing becomes reasonably accepted as a theoretical basis for futures prices by the late 1940s (see Blau (1945) and Working (1948)).[4] The formalization of arbitrage pricing theory for futures and forwards was finalized in the 1970s in a series of papers by Black (1976), Merton (1977), and Harrison and Kreps (1979). Cox, Ingersoll and Ross (1981) discuss the distinction between forward prices and futures prices, and the impact on futures prices of time varying interest rates. Hilliard and Reis (1998) provide the final theoretical steps when they discuss the pricing of commodity futures contracts in a stochastic interest rate setting. They present a model for futures prices using the Hull and White (1990) model for interest rate evolution.

The theoretical difficulty of correctly pricing futures or forward contracts is much less than that of pricing options, hence one might suspect that market participants have been pricing futures contracts well for centuries. However, proving, or disproving, the efficiency of futures/forward markets for *commodities* in an historical context is fraught with difficulties. Storage costs and convenience yields are problematic to calculate, with the information at hand today. For example, Bell, Brooks, and Dryburgh (2007) are forced to argue that, in the 13th and 14th century English wool market, storage costs were 'small' and the convenience yield was 'negligible'. In addition they find that (p. 368): 'for the vast majority of contracts, (the future price) is substantially below (the spot price) and therefore employing (the spot-future parity relation) will yield a negative (interest) rate.' Wakita (2001) lacks information on interest rates, storage, and transport costs for the Dojima rice market, and instead examines the seasonal pattern of the futures premium from 1760 to 1864.

Although single-stock futures have not been widely used throughout history they permit the testing of no-arbitrage futures pricing much more cleanly than with commodity futures. The advantages are that financial assets are not costly to store (hence storage costs need not be known), nor do they offer a convenience yield (with the exception of easily treatable

[4] Although we have a good idea of the state of knowledge in western financial markets we do not know how Japanese investors perceived the relation between spot and futures prices. Our research assistant was unable to locate any Japanese language treatises on futures pricing published in the early 20th century.

dividend payments). For a financial asset, the forward price should be the future value (at the maturity of the contract) of the current spot price, less the future value of any dividends which occur between the valuation date and the maturity of the contract:

$$F_T = \frac{S - PV(dividends)}{d(T)} \tag{1}$$

where F_T is the forward price for delivery at time T, S is the current spot price, and $d(T)$ is the discount factor for time T, i.e. $e^{-r(T)T}$ where $r(T)$ is the interest rate for maturity date T. In perfect and frictionles markets, the failure of this formula to hold results in an arbitrage opportunity, whereby a trader can either buy the underlying security with borrowed money and take a short forward position agreeing to sell the underlying in the future, or short sell the underlying security, agreeing to buy the security back in the future using a long forward position. For the 1920s Tokyo Stock Exchange, where the spot market was of minor importance, arbitrage could have been performed by taking a long position in one futures contract, coupled with a short position in the other contract. To ensure that the arbitrage profit was realised, the investor would also have had to enter into a forward rate agreement to lock in a rate of interest between the two maturity dates.[5]

The problem in evaluating the pricing of financial futures is that (modern) financial futures markets began to open at the same time as academics were finalizing no-arbitrage models of futures pricing. Interest rate futures debuted in October 1975 on the Chicago Board of Trade, and Treasury bill and bond futures were listed in 1976 and 1977 respectively. Futures on stock indices only commenced in the U.S. in 1982 on the Kansas City Board of Trade and the Chicago Mercantile Exchange (see Whaley (2006) p. 17). We cannot reliably test the precision of models with data collected after the models have been developed, since the data may have been 'contaminated' by the model. Prices may agree with model prices since market participants may trade using the model as a reference point. Our analysis of

[5]If forward rate agreements were unavailable (we find no mention of them), a synthetic forward rate agreement could have been created by trading short term bills. Most Japanese government debt was issued via long-term bonds, hence the short selling of bills may have been difficult and/or costly at this time. Therefore an 'arbitrageur' may have been exposed to some interest rate risk from carrying out a cross-trade on forwards.

the TSE in the 1920s permits us to assess the validity of no-arbitrage futures pricing with data that cannot have been influenced by the subsequent development of the pricing theory.

II Data

We obtain prices from *The Japan Times and Mail*, an English-language Tokyo daily newspaper, which reports 1-month, 2-month, and 3-month futures prices of a selection of around 40 to 50 equity securities. It appears that the newspaper reported prices of the largest and most heavily traded securities. The newspaper does not report spot prices and only reports transaction prices, no bid or ask quotes are available. If there was no trade on a particular day the price is reported as missing. There is only one price reported per futures contract per day. The newspaper does not specify which price it reports if there was more than one transaction per day, although the price does not appear to be an average price for the day. For the remainder of the paper we assume that the reported price is the last price of the day.[6] We collect daily prices on 29 of the most frequently traded equities from this newspaper (see Appendix A for details) between January 6, 1920 and August 28, 1923. We double-check our prices against those in the *Yomiuri Shimbun*, a Japanese-language daily newspaper, to eliminate typographical errors. We obtain data on dividend payments and calls of capital (of partially paid shares) from the 1925 and 1926 issues of *Kabukai 20nen* (20 years of the stock market).

Although the firms in our sample have not been randomly drawn from the population of all TSE-listed long-term futures, the lack of comprehensive price quotes for the whole market precludes us from doing otherwise. For example, *Asahi Shimbun* and *Yomiuri Shimbun*, leading Japanese-language daily newspapers, have only slightly more futures listed (and somewhat different coverage) than *The Japan Times and Mail*. *Kabukai 20nen* covers more of the securities listed on the TSE, but far fewer than the number of listings reported by Hamao et al. (2009). The TSE itself only began publishing official price lists in 1949.

[6]Our results would not change if the prices reported were for another point in time, e.g. the last transaction price before noon.

We collect interest rates at a daily frequency from *Yomiuri Shimbun*. This newspaper reports the lowest and the average overnight interest rate and the lowest and average one month interest rate. We assume that the interest rate on maturities between one day and one month can be linearly interpolated, and furthermore that interest rates for frequencies longer than one month are equal to the one month rate.

III Results

To assess the efficiency, or otherwise, of the TSE futures market we test the no-arbitrage relationship between prices of different maturities written on the same underlying asset. Since the TSE did not require margin calls the pricing of forwards and futures is identical. In the absence of dividends:

$$F_T = \frac{d(t)}{d(T)} F_t$$

where F_t is the futures price for delivery at time t, F_T is the futures price for delivery at (the later) time T, both prices observed simultaneously, and $d(\tau)$ is the discount factor for maturity τ.

We compare pairs of futures prices (of different maturities) for each firm, observed on the same day. Given the potential availability of 1 month, 2 month, and 3 month futures prices we can, if data exist for a given day, compare 1 month futures prices to 2 month futures prices, 2 month futures to 3 month futures, and 1 month futures to 3 month futures. In an efficient market the longer maturity futures price should be equal to the shorter maturity futures price plus interest.

We filter our data to preclude comparison of futures prices which were not equally affected by dividends. Dividend dates can be placed based on large positive differences between 1 and 2 month futures prices that persist for a whole month which we double check with dividend data from *Kabukai 20nen*. We also remove pairs where there was clearly a large predictable shift in stock value - which appear to have been caused by capital restructurings (e.g. a call of unpaid capital on a partly paid share) that we have been unable to precisely date with

Kabukai 20nen.

For each pair of contracts, we calculate pricing errors by taking the difference between the observed futures price (for the longer term contract) and the predicted price for the longer term contract (given the observed shorter term futures price and the interest rate) and dividing by the observed longer maturity futures price:

$$\epsilon = \frac{F_T - \frac{d(t)}{d(T)} F_t}{F_T}. \tag{2}$$

We square the calculated errors, and calculate the mean squared error (MSE) for a particular firm and a particular pair of futures in every month. We then take the square root to obtain root mean squared errors (RMSEs) month by month. Finally, we take the (equally weighted) average of the RMSEs across months (to get average RMSEs, or ARMSEs). The results are given in Table I.

We find large differences in mispricing across firms. The ARMSEs (with all contract pairs considered for a particular security) range from 0.7% for the Tokyo Stock Exchange (partly paid), to 3.0% for Toa Milling, the average (across firms) ARMSE is 1.7% when we consider all contract pairs.[7] Contract pairs that are only one month apart (1-2 month and 2-3 month) have similar average levels of mispricing, 0.9% and 1.0% respectively, whereas the further apart contract pairs (1-3 month) have a substantially higher level of mispricing, 2.4%.

A Constant Volatility Asynchronicity Correction

Since our observed data are transaction prices that are unlikely to be synchronous, we use a simulation exercise to measure the fraction of the observed mispricing that can be plausibly attributed to the unavoidable intra-day asynchronicity that we are forced to deal with. To do this we generate (time-stamped) transactions data for the futures prices, construct daily price series that use the last transaction price of the day, and compute mispricing measures using the constructed daily prices.

[7] The stock exchange was itself a publicly traded company.

First note that if futures contracts, with different delivery dates, are priced correctly at a moment in time (but possibly observed at different times during the same day) then the calculated pricing error will be $\epsilon = \frac{S_T - S_t}{S_T}$. For each firm-contract pair we do the following:

1. generate series of trade times for the near- and long-maturity contracts $(N1, N2, \dots)$ and $(L1, L2, \dots)$ given a Poisson intensity of trade arrival. This procedure may generate multiple trades per day.

2. generate series of spot prices for both the near- and long-maturity contracts $(S_{N1}, S_{N2}, ...)$ and $(S_{L1}, S_{L2}, ...)$ assuming that stock prices follow a Geometric Brownian motion. We then construct last-price-of-the-day spot price series for both contracts,$(S_{n1}, S_{n2}, ..., S_{n1339})$ and $(S_{l1}, S_{l2}, ..., S_{l1339})$ using the prices generated in the previous step.

3. calculate the mispricing errors as $\epsilon_j = \frac{S_{lj} - S_{nj}}{S_{lj}}$.

4. calculate the RMSE for this mispricing pair over one month's generated data.

We repeat this exercise 1000 times for each firm-contract pair. For each firm we use the volatility, σ_s, that we observe over the full sample of the data to generate the simulated stock prices, and we assume that σ_s is constant.[8] To calculate σ_s, we first calculate the spot price implied by the observed one month futures price, $S = F_T d(T)$. We remove months in which dividends or capital operations would have affected the one month futures price. Once we obtain a sequence of implied spot prices, we calculate returns. We calculate the standard deviation of these daily returns which we scale up to an annual volatility figure by multiplying by $\sqrt{250}$, the average number of trading days in a year. We choose the Poisson trade arrival intensity to match the observed frequency of days with no-trades being observed for the particular firm-contract pair considered.

Since we have generated data for which, by definition, the spot-future parity relation holds exactly at an instant in time, the average (over the 1000 repetitions) RMSE for each firm-contract pair is the measured mispricing (in any month) that is likely to be due to

[8] We need to infer spot prices since the spot market was much smaller than the futures market, and no spot prices were reported in the sources we have consulted.

asynchronous data, if all trades occur randomly. If all observed prices of different maturity futures (on the same underlying) occurred at the same time of the day, for example if all observed prices were arbitrage transactions, then no adjustment for asynchronous data would be warranted and the observed RMSEs are the appropriate measure of mispricing. In reality some proportion of trades will be due to arbitrage trades, and some due to other factors. Therefore the observed mispricing is an upper bound on mispricing and the observed mispricing less the simulated mispricing (which we term the 'residual' mispricing) will be a lower bound on mispricing. We average the simulated monthly RMSEs to obtain simulated ARMSEs, and then calculate 'residual' mispricing as:

$$mispricing_{resid} = ARMSE_{observed} - ARMSE_{simulated}.$$

The residual mispricing, averaged across all firms and all contract pairs, is less than 0.1%.[9] This mispricing for the 1-2 month and 2-3 month pairs is negative on average, which indicates that not all trades occurred at random times within a day, and is indirect evidence that some arbitrage trading occurred. The asynchronicity adjustment leaves a mispricing of 0.7% for the 1-3 month pairs, and some combination of investor error and transaction costs seems to have occurred for these futures. One possibility is that hedging two months of interest rate risk was costly or impossible in early twentieth century Japanese markets.

We perform one sided t-tests for whether the observed ARMSE is larger than the simulated ARMSE. If we can reject that the observed ARMSE is equal to the simulated ARMSE we bold the residual mispricing number in the table. We see that for 15 of the 29 1-3 month pairs the observed ARMSE is statistically larger than could be explained by pure asynchronicity arguments. None of the other futures' pairs mispricing are statistically different from asynchronicity measurement issues.

[9] The mispricing in the 'all' column of Tables I and II is constructed as follows: calculate all pricing errors in that month for a firm, regardless of contract pair. Use all pricing errors to create a monthly observed RMSE. Simulate a set of monthly RMSEs where there are three contracts, and all pairings are considered. Finally, subtract the simulated ARMSE from the observed ARMSE.

B Time-Varying Volatility Asynchronicity Correction

The results we present in Table I use the assumption that the volatility of stock prices, which influences measured mispricing in a situation with asynchronous prices, was constant through time. In reality, volatility was much higher in the early months of our sample (as prices dropped quickly in early 1920 due to a particularly sharp post-war recession) than in the later months. We therefore redo our simulation analysis, month by month, with a different volatility used for each firm-month. Since we use observed monthly volatilities for our simulation exercise, we only simulate data for a month which has at least three observations of returns. The necessity to have at least three return observations per month reduces our sample size by roughly one quarter. We present our results for time-varying volatility in Table II.

First of all, the observed ARMSEs do not change markedly, as the only effect on these is the reduction in the sample size. Secondly, the very volatile months in early 1920 no longer affect the volatilities used for the simulations in later months. Therefore, permitting time-varying volatility boosts the simulated RMSEs in early 1920 and reduces them for the rest of the sample, with the second effect dominating. Across all contract-pairs, and across all firms, the average 'residual' mispricing is 0.7% (compared to virtually zero in a constant volatility setting). The average 'residual' mispricing for 1-2 month pairs and 2-3 month pairs is very close to zero and slightly negative, whereas for 1-3 month pairs it is 1.4% (up from 0.7% in a constant volatility environment).

With a time-varying volatility fully 20 of the 29 1-3 month futures pairs exhibit statistically significant residual mispricing, and the overall market residual mispricing of 1-3 month futures pairs, 1.4%, is statistically significant. Again, the mispricing does not appear to be an issue for other contract pairs.

A potential concern is that differences between the constant and time-varying volatility results are due to different samples, since we are forced to exclude around one quarter of all months in the time-varying case, due to insufficient return observations. Therefore, as a robustness check we repeat the constant volatility calculations, but restrict the sample to the same months that we use for the time-varying volatility calculations. The results are almost unchanged.

C Causes of Mispricing

We have so far measured the mispricing of futures contracts traded on the Tokyo Stock Exchange, and shown that much of the observed mispricing can be attributed to asynchronous data.

To investigate the mispricing further we run the following regression:

$$RMSE_{j,t} = \alpha + \beta_1 AVGT_j + \beta_2 \sigma_j + \beta_3 MARKCAP_j + \beta_4 TEXTILE_j + \beta_5 SUGAR_j + \epsilon_{j,t}.$$

where $RMSE_{j,t}$ is the observed RMSE for a particular futures pair in a particular month. $AVGT_j$ is a proxy for the liquidity of the firm's futures, σ_j is the volatility of the firm's stock in month t (ie. calculated on a constant volatility basis), $MARKCAP_j$ is the firm's log market capitalization, calculated as the natural logarithm of the average of the market capitalization in January 1920 and August 1923, in millions of yen. We also add two dummy variables for textile firms and sugar firms.[10]

To calculate $AVGT_j$ we proceed as follows: for each firm-day we calculate the number of futures contracts that exhibited at least one trade, $trades_{j,t}$ (ie. we observe a price for that future). Since there are 1, 2, and 3 month futures contracts, $trades_{j,t}$ can take on a value between zero and three. We then calculate the time series average of $trades_{j,t}$ and divide by three to obtain a liquidity measure for firm j, $AVGT_j$, which ranges from 0 to 1. The results of these regressions are given in Table III.

Panel A shows that less liquid futures (lower $AVGT$) tend to have a higher observed mispricing, probably due to more asynchronicity problems. In addition, firms that experience more volatility also tend to have more observed mispricing. The results are weakened with

[10]These are the largest industrial groups listed on the TSE. Textile firms seem to have been regarded as more risky than other securities since the overnight interest rates charged on loans with textile firms' securities as collateral were higher.

the inclusion of the 1-3 month futures pairs, which are poorly priced with the pricing difficult to explain. The coefficients on $AVGT$ and σ for the time-varying volatility situation (not shown) are slightly stronger. Our observed mispricing is likely to be an overestimate for firms which tend to have few trades in a day (lower $AVGT$), which means a larger expected time gap between observed prices, and whose spot price is likely to have substantially changed in an interval between trades (higher σ). Firms with a higher market capitalization tend to have a lower mispricing of their futures, perhaps since their firm is followed more closely by potential arbitrageurs. The industry dummies are not robustly associated with mispricing.

In Panel B, we perform the same regression for 'residual' mispricing. Again the results are slightly stronger if we use a time-varying volatility. We find that liquidity is no longer robustly associated with mispricing, which we interpret as evidence that our asynchronicity adjustment has removed much of the problem. Volatility now becomes strongly statistically significant, in a negative direction, perhaps because firms which have more volatile equity tend to be those followed more by arbitrageurs, who act to remove pricing errors.

The question, is a residual mispricing of 0.7% implausibly large, is a difficult one to answer since we do not have any information on the transaction costs faced by Japanese investors. To place the mispricing that we calculate for Japanese futures into perspective we perform the same exercise for the contemporary U.S. market.

IV U.S. data

To get a better idea of how well Japanese investors were pricing single-stock futures in the 1920s, we would like to compare mispricing then with mispricing today using a comparable market. Unfortunately, single-stock futures are not currently exchange traded in Japan. The Osaka Securities Exchange, the preeminent Japanese derivatives market, only trades index futures. Therefore we obtain single-stock futures prices from OneChicago, a U.S. based exchange, which trades over 1300 single-stock futures.[11] From the OneChicago dataset we

[11] The data are available at http://www.onechicago.com/?page_id=1339

take a selection of securities which have a similar frequency of trading to our Japanese data.[12] For each firm traded by OneChicago, we calculate $AVGTRADES_j$, using contracts of three months or shorter maturity, and select those 22 firms whose $AVGTRADES_j$ exceeds the minimum observed for the Japanese data (see Appendix B). Our OneChicago data covers the period 7 April 2008 to 15 January 2010.

We repeat our analysis with the OneChicago data. The U.S. securities are futures contracts, and we must therefore be concerned about interest rate variability and price-interest rate correlation that impacts the prices of the securities, given that OneChicago requires margin payments. Hence, if interest rates are non-deterministic, we would not expect to see futures prices following the simple pricing relationship of forward contracts. As a result, when comparing futures prices, we use the model of Hilliard and Reis (1998) to calculate pricing errors between futures prices (see Appendix C). We use a two step process to implement their model. In the first step we calculate the implied spot prices given the OneChicago futures prices, assuming the spot-forward pricing relation holds exactly. Since we are better informed regarding dividend payments for the OneChicago data, we include contracts affected by dividends, and hence infer the implied stock price as $S = F_T d(T) + PV(dividends)$. We use this in conjunction with the one month LIBOR rate data (a proxy for the short interest rate) to calculate the volatility of the short rate, the volatility of the stock returns, and the correlation between stock returns and the short rate.

In Hilliard and Reiss' model, the volatility of the maturity τ instantaneous forward interest rate is given by $\sigma_r e^{-\kappa_r(\tau-t)}$. We use the 3-6 month forward rate (inferred from 3 and 6 month LIBOR rates) as a proxy for the 3 month instantaneous forward rate. We can thus estimate κ_r as being $\hat{\kappa}_r = -4\log\left(\frac{\sigma_f}{\sigma_r}\right)$, where σ_f is the standard deviation of changes in the 3-6 month forward rate and σ_r is the standard deviation of changes in the one month spot rate. In the second step, we use these estimated parameters (σ_s, σ_r, κ_r and ρ) to calculate price differences consistent with the Hilliard-Reis model. We then calculate the mispricing errors.

[12]In general, the OneChicago market is less liquid than the Japanese market. This is probably due to the fact that in Japan during the 1920s the futures market was the principal means of trading equities, whereas in the U.S. market today single-stock futures are a niche market.

A Constant Volatility

Table IV contains the observed ARMSEs for the OneChicago data with an assumed constant volatility. Across all firm-pairs, the average ARMSE is 1.7%, which is equal to the figure we obtain for our Japanese data. We repeat the mispricing simulation exercise with the OneChicago data. After making the asynchronicity adjustment we can explain the mispricing of all contract pairs (on average) for the U.S., whereas we cannot explain the 1-3 month mispricing for Japan. The 1-3 month futures pairs are also the worst priced in the U.S. market. The 1-3 month contracts for Sears Holding (2.5%), Wells Fargo (1.8%), and Citigroup (0.8%) all exhibit substantial residual mispricing, although only Sears Holding's mispricing is statistically significant. Part of the explanation is that these contracts are especially illiquid. For Sears Holding, the 1 month and 3 month contracts only traded on the same day 22 times in our sample, for Wells Fargo 34 times, and for Citigroup, 55 times.

Trading in single stock futures is a fringe activity in U.S. financial markets, hence the markets are generally very illiquid. Given these illiquid markets, problems of asynchronous data are more severe in the modern U.S. than in the more liquid Tokyo marketplace of the 1920s, which was the largest securities exchange in Japan at the time. Since data issues are relatively more important for OneChicago investors, the 'raw' mispricing calculations overstate the mispricing in the U.S. market. U.S. investors' mispricing is indistinguishable from asynchronicity issues in all except the 1-3 month futures pairs for Sears Holding, Wells Fargo, and Citigroup. For Japan, almost all 1-3 month futures pairs had residual mispricing. The performance of investors has improved in modern markets.

B Time-Varying Volatility

We repeat the mispricing exercise of Table IV, but we allow the volatility used in the simulation exercise to vary from month to month. We present these results in Table V. The average observed mispricing is slightly higher than in Table IV (since the requirement of three return observations per month to estimate the volatility reduces the sample size by about one quarter). After making our asynchronicity adjustment we find that, on average across all firms, there was no mispricing for any of the contract pairs. However, our point estimate is that seven of the 22 firms experienced residual mispricing individually. Nonetheless, compared to 26 out of 29 TSE firms, the performance of U.S. investors is clearly superior when a time-varying volatility adjustment is used.

We again perform statistical tests of residual mispricing. We find that the futures of Citigroup, Goldman Sachs, Chicago Mercantile Exchange, and Sears Holding exhibit statistical mispricing. However, considering the mispricing over all 22 firms, we do not find that any of the futures pairs are mispriced to a statistically significant degree, in contrast to the evident mispricing of 1-3 month futures on the TSE.

The sample selection of months that permit the calculation of monthly volatility cannot explain the worse performance of time-varying volatility either. If we perform a constant volatility asynchronicity adjustment, but only for those months that we use in the time-varying volatility calculations, we again obtain very close results to the constant volatility adjustment with the full sample.

C Causes of Mispricing

To investigate which factors are correlated with mispricing in the U.S. market we repeat the cross-sectional regressions for the OneChicago data in Table VI.[13] Panel A shows that asynchronous data are also a problem with U.S. data, less liquid and more volatile stocks register more observed mispricing. The industry dummies are not robustly associated with mispricing, nor is firm size. We obtain quite high values of R^2 which suggest, data issues aside, that mispriced futures are identifiable. We believe this apparent predictability is solely due to asynchronous data. In Panel B, once we appropriately adjust for time mismatched data, all coefficients lose statistical power, and the R^2 decreases substantially. In other words, once the raw data are appropriately treated, mispricing cannot be predicted and arbitrage possibilities do not appear to exist.

[13] Data for market capitalisation is obtained from the CRSP database. To maintain comparability with the Japanese calculations, we average the capitalisations for each firm on 31 March 2008 (just prior to the start of our data set) and 31 December 2009 (just prior to the end of our sample period).

Although we can not find data on transaction costs for early 20th century Tokyo, we are able to obtain such data for the OneChicago market. We calculate the average bid-ask spread on the OneChicago single stock futures listed on August 4, 2010. The average spread is 0.21%. In addition there are brokerage charges. The OneChicago website lists 13 brokers who trade OneChicago products. Of these 13 we were able to find cost data for four of them.[14] Costs are usually presented as a dollar amount per futures contract (of 100 shares). The costs ranged from $0.85 per contract to $3.49 per contract. The average price of a contract in our dataset is $7997, which means that broker costs as a percentage of the average contract size range from 0.01% to 0.04%.

Given transaction costs of roughly one-quarter of one percent, the mispricing of Goldman Sachs becomes statistically indistinguishable from asynchronicity. The residual mispricing of Citigroup, Chicago Mercantile Exchange and Sears Holding remains. However, at a 5% level of significance one would not be surprised to find a small number of mispriced firms out of a sample of 22.

V Conclusion

At first glance, Japanese investors over the period 1920 to 1923 were able to price single-stock futures as well as contemporary U.S. investors. We calculate the average ARMSE of Tokyo Stock Exchange futures to be 1.7%, the same as with the OneChicago data. In addition, if we only compare futures contracts where the time to maturity differs by one month, the pricing performance of Japanese investors appears to dominate current U.S. investors.

However, since we work with transaction prices which are not measured at the same point in time, problems with asynchronicity are unavoidable. We adjust for asynchronicity issues using a simulation exercise. After an appropriate adjustment we find that U.S. investors were making pricing errors that were rarely different from those one would expect solely due to time mismatched data. Such an adjustment can explain much of the Japanese mispricing,

[14] We find data for Interactive Brokers, optionsXpress, Peregrine Financial Group, and TradeStation Securities.

but it cannot explain why Japanese investors badly misprice 1-3 month futures contracts.

The development of no-arbitrage pricing theory in the 1930s-1970s appears to have allowed modern investors to better price futures. Institutional factors may also have played a part. Interest rate forwards are available today (allowing pricing differentials to be hedged rather than speculated upon), and transaction costs in electronic markets are also likely to be lower, which will drive prices closer to model no-arbitrage ones.

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A Underlying stocks, Tokyo Stock Exchange 1920-1923:

Nippon Yusen Kaisha, Toyo Kisen Kaisha, Fuji Gas (fully paid), Fuji Gas (partly paid), Kanegafuchi Cotton (fully paid), Kanegafuchi Cotton (partly paid), Nisshin Cotton, Toyo Cotton, Dai Nippon Sugar, Ensuiko Sugar, Toyo Sugar, Tainan Sugar, Yoyohama Stock Exchange, Tokyo Stock Exchange (fully paid), Tokyo Stock Exchange (partly paid), South Manchuria Railroad, Hokkaido Coal Steamship, Tokyo Woollen Cloth, Toyo Muslin, Jomo Muslin, Tokyo Muslin, Dai-Nippon Fertilizer, Kinagawa Power, Nippon Kinematographe, Fuji Paper, Teikoku Hemp, Nippon Hemp, Nippon Milling, Toa Milling.

B Underlying stocks, OneChicago :

Apple, Research in Motion, Citigroup, Freeport-McMoRan Copper & Gold, Bank of America, J.P. Morgan, Google, Goldman Sachs, Amazon, Qualcomm, Nucor, Walmart, Exxon Mobil, Johnson & Johnson, Chicago Mercantile Exchange, Wells Fargo, Sears Holding, Morgan Stanley, U.S. Steel, Gilead Sciences, Intel, Microsoft.

C Hilliard-Reis futures price correction

Assuming that interest rates follow the process:

$$dr = \kappa_r(\theta(t) - r)dt + \sigma_r dW,$$

if we assume that stock prices are composed of two parts:

$$S = S^* + PV(dividends)$$

where $PV(dividends)$ represents dividends which will be received prior to the maturity of the futures contract, then the time T futures prices will be given by:

$$\frac{S^* D_1(T) D_2(T)}{d(T)}$$

where $d(T)$ is the discount factor appropriate for time T, and:

$$\begin{aligned} D_1(T) &= \exp\left[\frac{\rho\sigma_s\sigma_r}{\kappa_r}(T - H(T))\right] \\ D_2(T) &= \exp(-(H(T) - T)\frac{\sigma_r^2}{\kappa_r^2} - \frac{\sigma_r^2 H(T)^2}{2\kappa_r} \end{aligned}$$

where

$$H(T) = \frac{1 - e^{-\kappa_r T}}{\kappa_r}.$$

We can thus construct an analogous relationship to (2) as being:

$$\epsilon = \frac{F_T - \frac{D_1(T)D_2(T)}{d(T)}\left(\frac{d(t)}{D_1(t)D_2(t)}F_t + PV(div_t) - PV(div_T)\right)}{F_T}$$

where $PV(div_t)$ is the present value of dividends prior to maturity of futures contract t.

Table I - Futures Mispricing, Tokyo Stock Exchange 1920-23, Constant Volatility

We calculate pricing errors as the observed longer-duration futures less the predicted longer-duration futures (given the interest rate and the observed shorter-duration futures price) divided by the observed longer-duration futures. We calculate monthly root mean squared errors for each futures pair and then calculate an unweighted average across months to obtain average root mean square errors (ARMSE). We present results by duration of futures pairs. We calculate an unweighted average ARMSE across firms in the ‘Average’ row. We generate simulated monthly mispricing errors by assuming the futures pricing relation holds exactly, but different duration futures prices arrive at a constant intensity within the day. We calculate simulated ARMSEs using the same method and average over 1000 repetitions of the simulation. We report the ARMSE - ARMSE(simulated). For the simulation we assume security volatility is constant from 1920 through 1923. # observations is the number of days on which we observe both futures prices. If the observed ARMSE is larger than the simulated ARMSE (using a one-sided t-test) the net ARMSE (residual mispricing) appears in bold font.

	ARMSE				# observations				ARMSE - simulated ARMSE			
Firm	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3
NYK	0.014	0.008	0.020	0.008	1415	462	514	439	**0.008**	0.001	**0.014**	0.002
TKK	0.021	0.013	0.023	0.013	342	88	157	97	**0.007**	-0.001	**0.010**	-0.001
FG(f)	0.020	0.008	0.030	0.007	1497	476	527	494	0.011	-0.001	**0.022**	-0.001
FG(p)	0.012	0.007	0.018	0.008	1006	321	353	332	-0.002	-0.007	0.005	-0.005
KC(f)	0.013	0.007	0.019	0.008	1755	582	570	603	**0.005**	-0.002	**0.011**	0.000
KC(p)	0.011	0.006	0.016	0.007	1756	588	567	601	-0.016	-0.022	-0.011	-0.019
NC	0.011	0.006	0.017	0.006	1752	584	574	594	0.000	-0.006	**0.006**	-0.005
TC	0.018	0.008	0.029	0.007	1134	339	426	369	0.007	-0.004	**0.018**	-0.005
DNS	0.016	0.010	0.023	0.008	1525	490	521	514	**0.006**	-0.001	**0.013**	-0.002
ES	0.020	0.008	0.031	0.009	1362	427	476	459	0.009	-0.004	**0.020**	-0.002
Ty S	0.019	0.009	0.023	0.010	1261	361	473	427	0.007	-0.003	0.012	-0.002
Tn S	0.025	0.013	0.029	0.017	572	160	247	165	-0.063	-0.075	-0.057	-0.068
YSE	0.015	0.008	0.021	0.009	1615	511	547	557	0.001	-0.006	0.008	-0.005
TSE(f)	0.009	0.007	0.011	0.008	1744	598	560	586	-0.002	-0.004	0.001	-0.002
TSE(p)	0.007	0.006	0.009	0.006	1487	513	466	508	-0.004	-0.005	-0.001	-0.005
SMR	0.012	0.008	0.013	0.007	368	87	192	89	0.001	-0.002	0.003	-0.003
HCS	0.013	0.009	0.017	0.010	847	237	356	254	0.002	-0.002	**0.006**	-0.001
TWC	0.018	0.013	0.022	0.012	1207	373	442	392	0.002	-0.003	**0.007**	-0.004
Ty M	0.023	0.009	0.037	0.011	1254	403	436	415	0.009	-0.006	**0.022**	-0.004
JM	0.021	0.009	0.032	0.010	1398	439	479	480	0.007	-0.005	**0.019**	-0.003
Tk M	0.018	0.008	0.026	0.012	868	271	306	291	0.001	-0.009	0.009	-0.005
D-NF	0.019	0.010	0.025	0.018	969	290	388	291	-0.004	-0.013	0.002	-0.006
KP	0.011	0.007	0.015	0.009	857	232	360	265	0.000	-0.003	**0.004**	-0.002
NK	0.023	0.009	0.034	0.009	1180	355	426	399	0.008	-0.006	**0.020**	-0.005
FP	0.017	0.009	0.021	0.013	940	278	376	286	0.005	-0.003	**0.009**	0.000
TH	0.021	0.010	0.026	0.012	689	192	276	221	0.004	-0.007	0.010	-0.005
NH	0.023	0.011	0.033	0.011	485	132	204	149	0.005	-0.008	0.015	-0.008
NM	0.021	0.011	0.030	0.014	629	177	248	204	-0.005	-0.014	0.005	-0.011
Ta M	0.030	0.015	0.041	0.014	827	252	313	262	-0.001	-0.016	0.011	-0.016
Avg.	0.017	0.009	0.024	0.010					0.000	-0.008	0.007	-0.007

Table II - Futures Mispricing, Tokyo Stock Exchange 1920-23, Time-Varying Volatility

We calculate pricing errors as the observed longer-duration futures less the predicted longer-duration futures (given the interest rate and the observed shorter-duration futures price) divided by the observed longer-duration futures. We calculate monthly root mean squared errors for each futures pair and then calculate an unweighted average across months to obtain average root mean square errors (ARMSE). We present results by duration of futures pairs. We calculate an unweighted average ARMSE across firms in the 'Average' row. We generate simulated monthly mispricing errors by assuming the futures pricing relation holds exactly, but different duration futures prices arrive at a constant intensity within the day. We calculate simulated ARMSEs using the same method and average over 1000 repetitions of the simulation. We report the ARMSE - ARMSE(simulated). For the simulation we estimate volatility in each month, using observed returns from that month. # observations is the number of days on which we observe both futures prices. If the observed ARMSE is larger than the simulated ARMSE (using a one-sided t-test) the net ARMSE (residual mispricing) appears in bold font.

	ARMSE				# observations				ARMSE - simulated ARMSE			
Firm	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3
NYK	0.014	0.007	0.022	0.007	1133	377	408	348	**0.009**	0.001	**0.016**	0.001
TKK	0.021	0.012	0.025	0.012	221	62	97	62	0.007	-0.003	**0.011**	-0.004
FG(f)	0.021	0.007	0.033	0.007	1247	387	440	420	**0.014**	0.000	**0.026**	0.000
FG(p)	0.012	0.006	0.019	0.008	819	258	287	274	0.001	-0.006	**0.007**	-0.004
KC(f)	0.015	0.008	0.022	0.008	1366	457	441	468	**0.008**	0.000	**0.015**	0.002
KC(p)	0.012	0.006	0.018	0.007	1372	464	440	468	-0.001	-0.007	0.005	-0.006
NC	0.013	0.005	0.019	0.007	1445	471	478	496	0.003	-0.004	**0.009**	-0.003
TC	0.021	0.009	0.033	0.007	931	268	354	309	**0.012**	0.000	**0.024**	-0.001
DNS	0.017	0.010	0.024	0.007	1253	391	431	431	**0.008**	0.001	**0.017**	-0.001
ES	0.016	0.007	0.024	0.008	1021	331	360	330	**0.007**	-0.002	**0.015**	-0.001
Ty S	0.014	0.010	0.016	0.010	1097	323	402	372	0.004	-0.001	0.006	0.000
Tn S	0.024	0.012	0.029	0.016	496	143	208	145	-0.010	-0.018	-0.005	-0.016
YSE	0.017	0.008	0.022	0.009	1329	404	460	465	0.005	-0.004	0.011	-0.002
TSE(f)	0.009	0.006	0.011	0.009	1366	459	443	464	0.001	-0.001	0.003	0.001
TSE(p)	0.007	0.006	0.009	0.005	1228	420	390	418	-0.003	-0.005	0.000	-0.004
SMR	0.012	0.008	0.013	0.010	309	76	161	72	**0.006**	0.000	**0.007**	0.002
HCS	0.014	0.009	0.017	0.010	657	187	271	199	**0.005**	0.000	**0.010**	0.002
TWC	0.019	0.012	0.023	0.013	987	301	367	319	**0.006**	0.001	**0.010**	0.000
Ty M	0.026	0.008	0.042	0.012	1055	341	363	351	**0.016**	-0.001	**0.032**	0.001
JM	0.024	0.008	0.037	0.010	1152	352	399	401	**0.013**	-0.001	**0.026**	-0.001
Tk M	0.020	0.008	0.029	0.014	721	227	252	242	**0.009**	-0.003	**0.017**	0.002
D-NF	0.021	0.011	0.028	0.020	739	226	291	222	0.005	-0.005	0.013	0.004
KP	0.011	0.006	0.014	0.008	700	185	294	221	**0.004**	-0.001	**0.007**	0.001
NK	0.021	0.009	0.030	0.009	870	272	308	290	**0.011**	-0.001	**0.020**	-0.002
FP	0.019	0.009	0.023	0.014	793	228	318	247	**0.010**	0.001	**0.014**	0.005
TH	0.026	0.011	0.036	0.011	469	131	194	144	**0.014**	-0.002	**0.023**	-0.002
NH	0.030	0.009	0.047	0.011	350	96	146	108	0.016	-0.001	0.033	-0.003
NM	0.022	0.011	0.033	0.014	479	139	190	150	0.004	-0.006	**0.017**	-0.002
Ta M	0.034	0.016	0.047	0.015	688	212	254	222	0.014	-0.005	0.028	-0.005
Avg.	0.018	0.009	0.026	0.010					0.007	-0.002	**0.014**	-0.001

Table III - Determinants of Mispricing, Tokyo Stock Exchange 1920-23

Panel A : Observed RMSE

We regress the observed monthly RMSEs on various controls. AVGT is the time-series average number of futures prices observed on a particular day (ranges from 0 to 3). σ is the estimated annual volatility of the underlying stock, calculated on a constant volatility basis. Textiles and Sugar are dummy variables equal to 1 for all firms in those industries. Market Cap is the log of average market cap, where the average is taken over January 1920 and August 1923. T-stats appear in parentheses. n is the number of observations.

	constant	AVGT	σ	Textiles	Sugar	Market Cap.	R^2	n
All	0.080	-0.005	0.000	0.003	0.003	-0.004		
	(4.382)	(-1.146)	(0.143)	(1.386)	(1.149)	(-3.292)	0.023	1107
1 - 2	0.026	-0.005	0.001	-0.000	0.001	-0.001		
	(4.823)	(-3.656)	(0.779)	(-0.083)	(0.814)	(-2.550)	0.041	886
1 - 3	0.121	0.000	-0.001	0.005	0.005	-0.006		
	(4.042)	(0.008)	(-0.412)	(1.731)	(0.916)	(-3.276)	0.021	884
2 - 3	0.029	-0.006	0.003	-0.001	-0.001	-0.001		
	(4.604)	(-3.261)	(2.634)	(-0.862)	(-0.618)	(-1.929)	0.038	867

Panel B : ‘Residual’ RMSE

We regress the ‘residual’ RMSEs on various controls as in Panel A. We calculate the ‘residual’ RMSE as the observed RMSE for that month less the simulated RMSE, constructed with a constant volatility, for that month.

	constant	AVGT	σ	Textiles	Sugar	Market Cap.	R^2	n
All	0.073	0.001	-0.033	0.003	0.002	-0.003		
	(4.035)	(0.325)	(-14.494)	(1.457)	(0.808)	(-3.151)	0.177	1107
1 - 2	0.021	0.001	-0.032	0.000	-0.000	-0.001		
	(3.821)	(0.404)	(-35.173)	(0.067)	(-0.235)	(-2.185)	0.716	886
1 - 3	0.114	0.006	-0.034	0.005	0.004	-0.006		
	(3.833)	(0.840)	(-9.616)	(1.778)	(0.745)	(-3.179)	0.106	884
2 - 3	0.021	0.002	-0.029	-0.001	-0.002	-0.001		
	(3.251)	(1.103)	(-28.835)	(-0.648)	(-1.603)	(-1.929)	0.492	867

Table IV - Futures Mispricing, OneChicago Data, Constant Volatility

We calculate pricing errors as the observed longer-duration futures less the predicted longer-duration futures (given the interest rate and the observed shorter-duration futures price) divided by the observed longer-duration futures. We calculate monthly root mean squared errors for each futures pair and then calculate an unweighted average across months to obtain average root mean square errors (ARMSE). We present results by duration of futures pairs. We calculate an unweighted average ARMSE across firms in the 'Average' row. We generate simulated monthly mispricing errors by assuming the futures pricing relation holds exactly, but different duration futures prices arrive at a constant intensity within the day. We calculate simulated ARMSEs using the same method and average over 1000 repetitions of the simulation. We report the ARMSE - ARMSE(simulated). For the simulation we assume security volatility is constant from 2008 to 2010. # observations is the number of days on which we observe both futures prices. If the observed ARMSE is larger than the simulated ARMSE (using a one-sided t-test) the net ARMSE (residual mispricing) appears in bold font.

	ARMSE				# observations				ARMSE - simulated ARMSE			
Firm	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3
AAPL	0.010	0.009	0.009	0.011	608	384	124	100	-0.004	-0.003	-0.006	-0.003
RIMM	0.017	0.017	0.015	0.018	421	268	93	60	-0.007	-0.006	-0.009	-0.006
C	0.043	0.038	0.056	0.040	349	251	55	41	-0.004	-0.006	0.008	-0.008
FCX	0.021	0.021	0.022	0.019	288	183	58	34	-0.008	-0.007	-0.007	-0.010
BAC	0.025	0.026	0.020	0.019	288	204	49	31	-0.011	-0.009	-0.017	-0.017
JPM	0.016	0.016	0.017	0.019	245	142	56	38	-0.012	-0.011	-0.010	-0.009
GOOG	0.011	0.011	0.011	0.012	237	150	50	34	-0.004	-0.004	-0.005	-0.004
GS	0.018	0.017	0.020	0.016	266	171	51	38	-0.007	-0.007	-0.005	-0.008
AMZN	0.016	0.015	0.012	0.015	232	143	49	26	-0.005	-0.005	-0.008	-0.006
QCOM	0.011	0.011	0.011	0.010	196	121	43	17	-0.004	-0.004	-0.004	-0.005
NUE	0.015	0.013	0.021	0.011	168	92	36	16	-0.010	-0.011	-0.004	-0.014
WMT	0.007	0.007	0.006	0.004	163	112	26	3	-0.003	-0.002	-0.004	-0.005
XOM	0.010	0.009	0.009	0.006	159	109	33	12	-0.003	-0.003	-0.003	-0.006
JNJ	0.005	0.005	0.006	0.004	131	96	23	9	-0.004	-0.003	-0.003	-0.005
CME	0.017	0.017	0.015	0.023	122	70	30	16	-0.009	-0.008	-0.011	-0.002
WFC	0.026	0.018	0.043	0.025	128	52	34	8	0.000	-0.007	0.018	0.001
SHLD	0.032	0.027	0.053	0.033	126	84	22	16	0.004	-0.002	**0.025**	0.006
MS	0.025	0.030	0.023	0.031	123	78	26	11	-0.014	-0.007	-0.014	-0.007
X	0.026	0.024	0.023	0.009	110	89	10	3	-0.004	-0.005	-0.007	-0.020
GILD	0.011	0.011	0.009	0.007	132	89	23	15	-0.003	-0.003	-0.004	-0.007
INTC	0.014	0.011	0.015	0.013	72	45	8	6	-0.003	-0.005	-0.001	-0.003
MSFT	0.011	0.012	0.006	0.009	85	51	24	5	-0.004	-0.002	-0.008	-0.005
Avg.	0.017	0.017	0.019	0.016					-0.005	-0.005	-0.004	-0.006

Table V - Futures Mispricing, OneChicago Data, Time-Varying Volatility

We calculate pricing errors as the observed longer-duration futures less the predicted longer-duration futures (given the interest rate and the observed shorter-duration futures price) divided by the observed longer-duration futures. We calculate monthly root mean squared errors for each futures pair and then calculate an unweighted average across months to obtain average root mean square errors (ARMSE). We present results by duration of futures pairs. We calculate an unweighted average ARMSE across firms in the 'Average' row. We generate simulated monthly mispricing errors by assuming the futures pricing relation holds exactly, but different duration futures prices arrive at a constant intensity within the day. We calculate simulated ARMSEs using the same method and average over 1000 repetitions of the simulation. We report the ARMSE - ARMSE(simulated). For the simulation we estimate the volatility in each month. # observations is the number of days on which we observe both futures prices. If the observed ARMSE is larger than the simulated ARMSE (using a one-sided t-test) the net ARMSE (residual mispricing) appears in bold font.

	ARMSE				# observations				ARMSE - simulated ARMSE			
Firm	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3	All	1 - 2	1 - 3	2 - 3
AAPL	0.010	0.009	0.009	0.011	608	384	124	100	-0.003	-0.001	-0.005	-0.002
RIMM	0.017	0.017	0.015	0.018	421	268	93	60	-0.004	-0.003	-0.008	-0.003
C	0.044	0.039	0.059	0.043	336	247	49	38	**0.036**	**0.031**	**0.050**	**0.034**
FCX	0.023	0.023	0.024	0.019	273	168	58	34	-0.018	-0.016	-0.015	-0.022
BAC	0.028	0.030	0.019	0.018	216	146	42	24	0.005	0.008	-0.001	-0.001
JPM	0.018	0.018	0.019	0.019	229	136	50	34	-0.011	-0.009	-0.006	-0.008
GOOG	0.012	0.012	0.010	0.011	228	147	47	31	-0.014	-0.013	-0.015	-0.017
GS	0.018	0.017	0.021	0.018	266	171	51	38	**0.006**	**0.005**	0.007	0.002
AMZN	0.016	0.015	0.012	0.015	232	143	49	26	-0.005	-0.004	-0.011	-0.006
QCOM	0.012	0.012	0.011	0.010	180	105	43	17	-0.007	-0.006	-0.008	-0.010
NUE	0.016	0.014	0.021	0.011	168	92	36	16	0.003	0.002	0.008	-0.001
WMT	0.008	0.008	0.007	0.004	141	101	21	3	-0.002	-0.003	-0.003	-0.006
XOM	0.011	0.010	0.010	0.008	150	105	28	12	-0.014	-0.015	-0.016	-0.019
JNJ	0.006	0.006	0.009	0.004	108	83	16	6	-0.003	-0.002	-0.002	-0.006
CME	0.019	0.018	0.020	0.024	83	47	21	12	**0.008**	**0.007**	0.007	**0.011**
WFC	0.023	0.022	0.026	0.016	41	27	9	4	0.009	0.008	0.007	-0.002
SHLD	0.039	0.033	0.067	0.054	98	65	16	13	**0.031**	**0.024**	**0.059**	**0.044**
MS	0.037	0.046	0.038	0.064	100	70	15	9	0.014	0.024	0.012	0.038
X	0.022	0.018	0.021	0.016	82	61	10	3	0.000	-0.003	0.005	0.000
GILD	0.013	0.013	0.010	0.007	124	83	23	15	-0.012	-0.011	-0.016	-0.020
INTC	0.017	0.015	0.019	0.014	46	31	8	4	-0.028	-0.029	-0.008	-0.038
MSFT	0.008	0.008	0.005	0.010	68	42	20	4	-0.019	-0.018	-0.029	-0.017
Avg.	0.019	0.018	0.020	0.019					-0.001	-0.001	0.001	-0.002

Table VI - Determinants of Mispricing, OneChicago Data

Panel A : Observed RMSE

We regress the observed RMSEs on various controls. AVGT is the time-series average number of futures prices observed on a particular day (ranges from 0 to 3). σ is the estimated annual volatility of the underlying stock, calculated on a constant volatility basis. Tech and Finance are dummy variables equal to 1 for all firms in those industries. Market Cap is the log of average market cap on 31 March 2008 and 31 December 2009. T-stats appear in parentheses. n is the number of observations.

	constant	AVGT	σ	Tech	Finance	Market Cap.	R^2	n
All	-0.004	-0.009	0.033	-0.000	-0.004	0.000		
	(-0.167)	(-1.283)	(4.807)	(-0.166)	(-1.319)	(0.195)	0.208	451
1 - 2	-0.010	-0.009	0.032	0.000	-0.003	0.001		
	(-0.447)	(-1.141)	(4.662)	(0.211)	(-1.109)	(0.497)	0.176	440
1 - 3	0.004	-0.009	0.042	-0.004	-0.007	-0.000		
	(0.103)	(-0.984)	(3.406)	(-1.699)	(-1.246)	(-0.166)	0.215	259
2 - 3	0.016	-0.003	0.027	0.003	0.002	-0.001		
	(0.459)	(-0.259)	(2.648)	(1.302)	(0.484)	(-0.594)	0.195	207

Panel B : ‘Residual’ RMSE

We regress the ‘residual’ RMSEs on various controls as in Panel A. We calculate the ‘residual’ RMSE as the observed RMSE for that month less the simulated RMSE, constructed with a constant volatility, for that month.

	constant	AVGT	σ	Tech	Finance	Market Cap.	R^2	n
All	-0.007	-0.006	-0.001	-0.000	-0.004	0.000		
	(-0.279)	(-0.866)	(-0.139)	(-0.160)	(-1.322)	(0.262)	0.016	451
1 - 2	-0.016	-0.003	-0.001	0.000	-0.003	0.001		
	(-0.690)	(-0.395)	(-0.076)	(0.216)	(-1.171)	(0.641)	0.012	440
1 - 3	0.006	-0.011	0.007	-0.004	-0.007	-0.000		
	(0.139)	(-1.119)	(0.582)	(-1.650)	(-1.194)	(-0.189)	0.022	259
2 - 3	0.019	-0.003	-0.007	0.003	0.002	-0.001		
	(0.529)	(-0.339)	(-0.711)	(1.296)	(0.479)	(-0.652)	0.016	207