# Long Range Dependence and Structural Breaks in the Gold Markets

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**Long Range Dependence and Structural Breaks in the Gold Markets**

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**Abstract**: The price of gold and its determining factors have been studied extensively in the literature. However, there is a lack of research on structural break in the long memory of the gold markets. This paper examines the long memory properties of gold prices. In particular, it attempts to test the stability of the long range dependence of gold returns and volatility. The results suggest that long memory exists in gold returns and volatility, and that the volatility of daily gold futures returns can be characterized by a hyperbolic decaying long memory process. Three episodes of structural breaks are found.

**Keywords**: Long Memory; Modified R/S Statistic; FIGARCH; Spot Gold; Gold Futures
**JEL Classification**: C22.

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## 1. Introduction

The dynamics of the gold market has long been studied. For example, Tandon and Urich (1987) found that the daily gold price is influenced by the unanticipated factors of U.S. money supply and producer price index announcements. Bailey (1988) concluded that an increase in money supply (according to weekly updates) raises the volatility of the price of gold. Kitchen (1996) found that the price of gold is positively related to changes in government deficit projections. Cai *et al.* (2001) analyzed gold futures tick-by-tick data and found that massive sales by central banks, fluctuation in interest rates and oil prices, as well as socio-economic tensions in South Africa contribute to the price fluctuations, while the unemployment rate, GDP, CPI, and household income of the United States significantly impact the dynamics of return volatility. Moreover, strong intraday periodicity overshadows the long memory feature of gold futures.

While the long-range dependence in market returns and volatility have been well explored, studies on the stability of the long memory process are scant (Banerjee and Urga, 2005). Among the few, Cheung and Lai (1993) examined the sensitivity of the long memory test in the gold market and found that the gold market is unstable over time. Beran and Terrin (1996) found that small changes in the long memory parameter have strong implications on the long-term behavior of the process. Granger and Terasvirta (1999) showed that the estimate of the long memory parameter is closely connected to the frequency of regime switches and the spots at which they occur in the sample. Gourieroux and Jasiak (2001) argued that processes with infrequent regime switches might generate a long memory effect in the autocorrelation function. Dittmann and Granger (2002) showed that the existence of structural breaks leads to an under-estimation of the long memory parameter.

Mikosch and Starica (2004) evaluated the possible long memory in volatility in the presence of a structural break. Chan and Young (2006) and Chan and Feng (2012) studied the jump behavior of copper and stock markets, respectively.

Seeing this gap in the literature, this paper studies the long memory property in the returns and volatility time series with respect to the gold markets. Following Chong *et al*. (2012), who found long memory in the volatility of the diamond market, a modified rescaled range (R/S) statistic of Lo (1991) was used to test for long memory in the gold market. Strong evidence in support of long memory in gold returns was found. In particular, this paper also examined the dynamics of the long memory parameter. This paper concludes that there are three structural breaks in the gold market in our sample, namely, the Middle East oil price crisis in 1979, the turmoil in South Africa in 1987 and the surging demand in gold from China and India since 2007. The structure of the paper is organized as follows: Section 2 presents the modified R/S statistic and FIGARCH model. Section 3 examines and tests for long memory properties in the gold market. Section 4 reports empirical evidence for structural breaks in the degree of long memory in gold returns and price volatility. Section **5** concludes the paper.

## 2. Methodology

Long range dependence in asset returns and volatility has attracted academic attention over the past two decades. Ding *et al*. (1993) examined the persistence of long memory in stock market volatility. Baillie *et al*. (1996) provided evidence of long-range dependence in the volatility of exchange rates. Baillie *et al.* (2002) found long memory in both the conditional mean and the variance of inflation rate.

The classical R/S analysis was first introduced by Hurst (1951) and uses the following definitions:

- A stationary stochastic process $X_t$ is defined as a long memory process if there exists a real number $\alpha \in (0,1)$ and a constant C>0 such that $\lim_{k \to \infty} \rho(k)/[Ck^{-\alpha}] = 1$, where $\rho(k)$ is the autocorrelation function.
- The Hurst exponent H, which represents the long-memory property of the time series, is defined as $H = 1 - \frac{\alpha}{2}$.

Long memory occurs when $H \in (\frac{1}{2}, 1)$. Thus, a time series is said to exhibit long memory if there is a slow hyperbolic decay in autocorrelations.

- If H>1, the series is non-stationary;
- If $H \in (0, \frac{1}{2})$, the series is anti-persistent.

Subsequently, the classical R/S analysis was refined by Mandelbrot (1972) and Lo (1991). The modified rescaled range (R/S) statistic of Lo (1991) was applied to test for long memory in a stationary time series $X_t$ with a sample size N in this paper. The modified rescaled range statistic is defined as

$$\hat{Q} = \frac{1}{\hat{s}(q)}\left[\max_{1 \le t \le N} \sum_{k=1}^{t} \left(x_k - \bar{x}\right) - \min_{1 \le t \le N} \sum_{k=1}^{t} \left(x_k - \bar{x}\right)\right], \quad (1)$$

where

$$\hat{s}^2(q) = s^2 + 2\sum_{k=1}^{q} w_k(q)\gamma_k \; ; \tag{2}$$

$$s = [\frac{1}{N}\sum_{t=1}^{N}(x_t - \bar{x})^2]^{1/2} \; ; \tag{3}$$

$$\bar{x} = \frac{1}{N}\sum_{t=1}^{N} x_t \; ; \tag{4}$$

$$w_k(q) = 1 - \frac{k}{q+1}, q < N \tag{5}$$

and

$$\gamma_k = \frac{1}{N}\left[\sum_{i=k+1}^{N}(x_i - \bar{x})(x_{i-k} - \bar{x})\right] \tag{6}$$

The null hypothesis of no long-range dependence can be tested using the asymptotic distribution

$$P[\hat{Q} \le x] = 1 - 2\sum_{n=1}^{\infty}(4x^2n^2 - 1)e^{-2x^2n^2} \tag{7}$$

against the composite alternative of long memory. If the truncation lag, denoted by $q$, is equal to zero, the modified R/S statistic is reduced to Hurst's R/S statistic.

The modified R/S statistic is robust to short-term dependence and conditional heteroscedasticity. It has high power against certain long-range dependence alternatives and has been extensively used to detect the presence of long memory in various time series, including but not limited to the conditional variance of U.S. stock return indices (Crato and De Lima, 1994); stock market volatility (Breidt *et al.,* 1998); weekly stock returns in multiple countries such as Korea, Malaysia, Singapore and New Zealand (Sadique and

Silvapulle, 2001); long-range dependence in stock markets in China, Hong Kong and Singapore (Cajueiro and Tabak, 2004)

A FIGARCH model is estimated to determine the long memory parameter d, which characterizes the long memory property of hyperbolic decay in volatility.[2] The FIGARCH model was introduced by Baillie *et al*. (1996). It is an extension of the GARCH model of Bollerslev (1986) and the IGARCH model of Engle and Bollerslev (1986). It has been applied to model the long memory behavior of exchange rates (Baillie *et al.*, 1996), commodity futures (Crato and Ray, 2000), inflation rates (Baillie *et al*., 2002) and crude oil futures (Martens and Zein, 2004).

A FIGARCH (p, d, r) model for $\{\varepsilon_t\}$ is defined by

$$\phi(L)(1-L)^d \varepsilon_t^{\,2} = \omega + [1-\beta(L)]\nu_t , \qquad (8)$$

where d is the fractional integration parameter,

$$\phi(L) = [1-\alpha(L)-\beta(L)](1-L)^{-1} , \qquad (9)$$

$$\alpha(L) = \alpha_1 L + \alpha_2 L^2 + \cdots + \alpha_r L^r , \qquad (10)$$

$$\beta(L) = \beta_1 L + \beta_2 L^2 + \cdots + \beta_p L^p . \qquad (12)$$

$$\nu_t = \varepsilon_t^{\,2} - \sigma_t^{\,2} . \qquad (13)$$

The conditional variance of FIGARCH (p, d, r) is given by

[2] For other estimation methods for d, one is referred to Chong (2000) and Chong and Hinich (2007, 2009).

$$\sigma_t{}^2 = \omega[1-\beta(1)]^{-1} + \lambda(L)\varepsilon_t{}^2, \tag{14}$$

where $\lambda(L) = \{1-[1-\beta(L)]^{-1}\phi(L)(1-L)^d\} = \lambda_1 L + \lambda_2 L^2 + \cdots$ and $\lambda_k$ is non-negative.

## 3. Data and Results

### 3.1. Data

The daily prices of spot gold span the period from August 2, 1976 to July 14, 2008 inclusive. The sample of gold futures market covers the period from January 2, 1979 to July 14, 2008 inclusive. All data was obtained from DataStream. Returns are defined as the first difference of the natural logarithm of gold prices:

$$R_t = \ln P_t - \ln P_{t-1}, \tag{15}$$

where $P_t$ is the corresponding price series. The samples contained 8335 observations of daily spot gold return and 7704 observations of gold futures return.

Davidian and Carroll (1987) suggested that the volatility of absolute returns is more robust to asymmetry and non-normality. Taylor (1986) presented evidence that absolute return based models generate better volatility forecasts than models based on squared returns. In this paper, absolute returns, squared returns, absolute deviation, and square mean deviation were all used to proxy for volatility. The square mean deviation and absolute deviation provide a better measure for volatility compared to absolute returns and squared returns. The summary statistics for spot gold and gold futures are reported in Table 1a and 1b respectively.

**Tables 1a and 1b about here**

The kurtosis values indicate that the unconditional distributions of these returns exhibit a thick tail. Among the four measures of volatility, the squared return and square mean deviations exhibit a higher degree of skewness and kurtosis relative to their absolute value counterparts.

### 3.2. Results of the Modified R/S statistic

The values of the modified R/S statistic calculated for squared returns, absolute returns, absolute deviation and square mean deviation of the spot gold and gold futures daily returns samples are reported in Table 2a and 2b respectively.

**Tables 2a and 2b about here**

A test for the null hypothesis of d=0 was performed using a 95 percent confidence interval [0.809, 1.862] of the modified R/S statistic.[3]

Teverovsky *et al.* (1999) showed that Lo's modified R/S statistic tended to under-reject the null hypothesis of no long memory. In view of this and to ensure robustness of this study, this paper reports the modified R/S statistics for a wide range of values of the truncation lag *q* up to a maximum of 100. The null hypothesis is rejected in all cases, which provides strong evidence of long memory in gold daily returns and volatility. The size of the statistic is reduced as the truncation lag increases. This is consistent with Teverovsky *et al.* (1999) in that the R/S statistic has the tendency of accepting the null hypothesis for large

[3] Critical values are given in Lo (1991).

truncation lags. Hence, the findings hold for different truncation lags and volatility measures.

### 3.3. Results of the FIGARCH Model

The estimated long memory parameter d for spot gold and gold futures of the FIGARCH (1, d, 1) model are reported in Table 3a and 3b respectively.[4]

**<u>Tables 3a and 3b about here</u>**

Table 3a shows that the estimated long memory parameter d of the FIGARCH (1, d, 1) model ranges from 0.2834 to 0.4115, while Table 3b shows that the estimated long memory parameter ranges from 0.2934 to 0.3575. In general, the value of d is consistently significant, indicating that the daily return and volatility of spot gold prices can be characterized by a hyperbolic decaying long memory process. The empirical evidence demonstrates the presence of an explicit long memory feature in gold daily returns and volatility.

### 3.4 Results over multiple frequencies

Estimations are undertaken over multiple frequencies. In terms of weekly data, 1668 weekly observations of the Gold Bullion LBM U$/Troy Ounce spanned the period from August 2, 1976 to July 14, 2008, and 1541 observations of the COMEX Gold Futures 100 oz rate spanned the period from January 8, 1979 to July 14, 2008. For monthly data, 391

[4] The FIGARCH(1,d,1)model is applied by following Baillie et al. (1996) in which a FIGARCH(1,d,1) model was used to exam the long memory of Deutschmark-U.S. dollar volatility.

monthly observations of Gold Bullion LBM U$/Troy Ounce that spanned the period from January 14, 1976 to July 14, 2008, and 355 monthly observations of COMEX Gold Futures 100 oz rate that spanned the period from January 14, 1979 to July 14, 2008 were used.

The results of Lo's modified R/S statistic for returns, squared returns, and absolute returns for weekly and monthly frequencies are reported in Table 4a and Table 4b, respectively. The null hypothesis was rejected for q=(0,2,5,10) in all cases of weekly returns. For monthly returns, the null hypothesis was rejected for q=(2,5) in all cases. Rejection of the null hypothesis implies a relatively strong self-similarity feature of the gold market.

**Tables 4a and 4b about here**

## 4. Structural Breaks in Long Memory

In this section, a forward rolling and a backward rolling test is employed to determine the stability of the long memory property in the gold market.

### 4.1. Forward Rolling Method

For the forward rolling procedure, the whole sample was split into several subsamples. The test is first performed on the first subsample. The data for the next five years are added to the first subsample to form a new subsample, and the test is administered on it. This process continues until the subsample incorporating the last observation is tested. The results of the modified R/S statistic with the forward rolling estimation for spot gold and gold futures are reported in Tables 5a and 5b, respectively.

**Tables 5a and 5b about here**

Regarding the null hypothesis of no long memory, the null hypothesis d=0 is not rejected in the first subsample, suggesting that the autocorrelation function in the seven-year period of 1976 to 1983 might not exhibit hyperbolic decay. However, the absence of long memory is mostly rejected when new data from subsequent years are included. This conflicting evidence on long memory in spot gold returns suggests that a structural break might have occurred during the period of 1983-1988.

The modified R/S statistic is also applied to the forward rolling data of absolute returns and the square mean deviation. In the gold futures market, the null hypothesis of d=0 is rejected for the full sample from January 2, 1979 to July 14, 2008, shown in Table 5b. Thus, the long memory pattern is consistently significant over the whole sample period. However, for all the sub-samples, the null hypothesis of a stationary series was not rejected. The results provide conflicting evidence for long memory in gold futures daily returns, which suggest that the autocorrelation function in the 24-year period from 1979 to 2003 might not exhibit hyperbolic decay. The results also imply that there might be structural breaks in the gold futures returns between 2003 and 2008.

To test for structural breaks in the volatility of gold futures, the second panel of Table 5b reports test statistics for the gold futures absolute returns, in which the null hypothesis of stationarity is rejected for all cases, providing strong evidence for long memory in volatility of gold futures. For the daily square mean deviation of gold futures, the null hypothesis is rejected in all cases except for the first seven-year sub-sample with a truncation point of q=100. Therefore, the long memory pattern in the volatility of gold futures is significant across the forward rolling samples. Weak evidence for a structural break of long memory in the volatility of gold futures is found for the sample period of 1988-1993.

### 4.2. Backward Rolling Method

The results for spot gold and gold futures under the backward-rolling test are reported in Table 6a and 6b respectively

**<u>Tables 6a and 6b about here</u>**

For the **spot gold return series**, the backward rolling process starts administering the test on the subsample from July 14, 2001 to July 14, 2008. The data for the previous five years are then added to form a new subsample. The backward rolling process continues until the subsample incorporating data at the beginning of the sample period is tested. Results in Table 6a show that the null hypothesis of d=0 is rejected by all subsamples except for the first three. This provides contradictory evidence for long memory in spot gold daily returns. Note that as the sample size grows, the long memory pattern in the subsamples becomes consistently significant. Therefore, a potential change point lies between 1986 and 1991.

For the **absolute return series**, the null hypothesis is rejected in all cases except for the subsample from July 14, 2001 to July 14, 2008 for q=100, and the sample from July 14, 1996 to July 14, 2008 for q=100. This lends support for the existence of long memory in the volatility of spot gold. For the daily square mean deviation, the null hypothesis is not rejected in the first two subsamples from July 14, 2001 to July 14, 2008and from July 14, 1996 to July 14, 2008 for q = 50 and 100. This suggests the presence of a structural break in 1991-1996.

For the **gold futures returns**, the backward rolling procedure is first performed on the data from the subsample from July 14, 1999 to July 14, 2008. The data for the previous five years from July 14, 1994 to July 14, 1999 are then added to form a new subsample. The backward rolling process continues until the sample containing data from January 2, 1979 is tested.

Estimates for the modified R/S statistic using daily returns are summarized in the first panel of Table 6b. The null hypothesis is not rejected in the following two periods: July 14, 1999 to July 14, 2008 and July 14, 1994 to July 14, 2008. For the subsample of July 14, 1989 to July 14, 2008, the null hypothesis is rejected only for q=100. For the sub-sample of July 14, 1984 to July 14, 2008, the null hypothesis is rejected for q=50 and 100. The results provide conflicting evidence for the existence of long memory in gold futures daily returns. As the sample size grows, however, the long memory pattern in the sub-samples becomes significant. The results suggest that a structural break took place between 1979 and 1984. The second panel reports the similar test statistics for the gold futures absolute returns, where the null hypothesis of stationary series is rejected in all cases except for the sub-series from July 14, 1999 to July 14, 2008 for q=100. This provides strong evidence for the existence of long memory in gold futures volatility. The results from third panel are obtained by using the gold futures daily square mean deviation, where the null hypothesis is not rejected in the first two sub-samples from July 14, 1999 to July 14, 2008 for q=100 and that of July 14, 1994 to July 14, 2008 for q=100. Therefore, the long memory characteristic in the volatility of gold futures is significant, and the results indicate a structural break in the long memory of the volatility of gold futures between 1989 and 1994.[5]

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[5] It is noteworthy that as the sample size increases, the long memory feature becomes significant in gold futures markets.

### 4.3. Evidence for Structural Breaks from the FIGARCH Model

In light of the results in the previous section, three events that might induce a structural break in the long memory properties of the gold markets were pinpointed and examined.

The first event is the Second Oil Crisis and the Middle East Crisis in 1979. The Second Oil Crisis occurred following the Iranian Revolution in 1978-1979, where a surge in oil prices drove a subsequent surge in gold prices. Moreover, the geopolitical turmoil in 1979, especially the Middle East Crisis, caused the demand for gold as a substitute for liquid assets to increase as investors around the world hedged their portfolios against increased perceived risk.

The second factor is the sociopolitical tension in South Africa in 1987. Specifically, the mining strike on August 9, 1987 might have led to a dramatic rise in gold price[6] following a surge in oil prices. This is consistent with the finding of Cai *et al.* (2001) on the positive correlation between oil price and gold price. The third event is the increasing demand for gold from China and India since 2007. The mammoth rise in the price of gold was largely due to the increasing demand for gold from these two largest emerging economies.

To test if there are structural breaks in spot gold returns and volatility in the aforementioned events, a FIGARCH (1, d, 1) model was estimated using three different sample splitting methods:

(i) August 2, 1976 to February 11, 1979; February 12, 1979 to July 14, 2008;

(ii) August 2, 1976 to August 9, 1987; August 10, 1987 to July 14, 2008;

(iii) August 2, 1976 to July 1, 2007; July 2, 2007 to July 14, 2008.

[6] In the same year, the heightened tension in the Middle East might have also increased the demand for gold.

The results for spot gold are reported in Table 7a. The sample skewness and kurtosis are reported. Results from the Ljung-Box portmanteau test for up to 20th-order serial correlation in standardized residual are also reported. Note that there is a noticeable difference between the long memory parameter d in different samples. In particular, there are changes in the long memory of returns in 1979 and 2007, while a shift in the long memory of volatility occurs in 1987.

To analyze the structural break in the long memory for the gold futures market at the potential break points of 1979, 1987, and 2007, the FIGARCH (1, d, 1) model was estimated utilizing subsamples determined by three different sample splitting methods:

(i) January 2, 1979 to February 11, 1979; February 12, 1979 to July 14, 2008;

(ii) January 2, 1979 to August 9, 1987; August 10, 1987 to July 14, 2008;

(iii) January 2, 1979 to July 1, 2007; July 2, 2007 to July 14, 2008.

The results for gold futures are shown in Table 7b, and support the previous explanations for structural breaks in the long memory in the gold futures market. The abnormal results in the sample from January 2, 1979 to February 11, 1979 might have been caused by the limited sample size of 29 observations.

**Tables 7a and 7b about here**

## 5. Conclusions

The gold market has experienced extreme volatility over the past decade. This paper revisited the long memory properties in the gold spot and futures markets. The results suggest that long memory properties exists in gold returns and volatility, and that the volatility of daily gold futures returns can be characterized by a hyperbolic decaying long memory process.

In addition, this paper contributes to the literature by developing a test for structural breaks of the long memory property in gold returns and volatility. Three episodes of structural breaks were found, their causes being the Middle East oil price crisis in 1979, the turmoil in South Africa in 1987, and the surging demand for gold in China and India since 2007. In view of the results in this paper, future research along this line on other commodity markets is anticipated.

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**Table 1a**: Summary statistics of spot gold daily returns, absolute returns, squared returns, absolute deviation and square mean deviation

| | $R_t$ | $\lvert R_t \rvert$ | $R_t^2$ | $\lvert R_t - \overline{R} \rvert$ | $(R_t - \overline{R})^2$ |
|---|---|---|---|---|---|
| Obs. | 8335 | 8335 | 8335 | 8335 | 8335 |
| Mean | 0.00011 | 0.00327 | 2.75E-05 | 0.00327 | 2.75E-05 |
| Maximum | 0.05302 | 0.07761 | 0.00602 | 0.07772 | 0.00604 |
| Minimum | -0.07761 | 0.00000 | 0.00000 | 2.1E-07 | 0.00000 |
| S.D. | 0.00524 | 0.00410 | 0.00012 | 0.00410 | 0.000117 |
| Skewness | -0.34813 | 3.91272 | 23.66 | 3.92991 | 23.7355 |
| Kurtosis | 19.08 | 34.20 | 957.28 | 34.4192 | 963.86 |
| Jarque-Bera | 899929.4 | 359297.4 | 3.17E+08 | 364291 | 3.2E+08 |
| P-value of the JB test | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |

**Table 1b**: Summary statistics of gold futures daily returns, absolute returns, squared returns, absolute deviation and square mean deviation

| | $R_t$ | $\lvert R_t \rvert$ | $R_t^2$ | $\lvert R_t - \overline{R} \rvert$ | $(R_t - \overline{R})^2$ |
|---|---|---|---|---|---|
| Obs. | 7704 | 7704 | 7704 | 7704 | 7704 |
| Mean | 8.28E-05 | 0.00335 | 2.75E-05 | 0.003356 | 2.75E-05 |
| Maximum | 0.04232 | 0.04380 | 0.00192 | 0.04388 | 0.001926 |
| Minimum | -0.04380 | 0.00000 | 0.00000 | 5.20E-06 | 0.00000 |
| S.D. | 0.00524 | 0.00403 | 8.94E-05 | 0.004024 | 8.94E-05 |
| Skewness | -0.12244 | 3.07855 | 10.05 | 3.08937 | 10.0429 |
| Kurtosis | 11.60 | 18.33 | 149.07 | 18.4026 | 148.89 |
| Jarque-Bera | 23786.83 | 87614.67 | 6978909 | 88409.13 | 6962088 |
| P-value of the JB test | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |

Notes: The Jarque-Bera test for normality distributed as Chi-square with 2 degrees of freedom. The critical value for the null hypothesis of normal distribution is 5.99 at 5% significance level.

**Table 2a**: The modified R/S statistic for spot gold daily returns, absolute returns, squared returns, absolute deviation and square mean deviation

| q | $R_t$ | $\lvert R_t \rvert$ | $R_t^2$ | $\lvert R_t - \overline{R} \rvert$ | $(R_t - \overline{R})^2$ |
|---|---|---|---|---|---|
| 0 | 2.3676* | 13.3309* | 7.9787* | 13.3272* | 7.9606* |
| 2 | 2.4320* | 10.6562* | 6.7756* | 10.6529* | 6.7642* |
| 5 | 2.4145* | 8.6039* | 5.6255* | 8.5993* | 5.6171* |
| 10 | 2.4176* | 6.9303* | 4.6645* | 6.926* | 4.6588* |
| 25 | 2.3397* | 5.0081* | 3.5245* | 5.0038* | 3.5210* |
| 50 | 2.3454* | 3.8405* | 2.8614* | 3.8368* | 2.8587* |
| 100 | 2.4197* | 2.8890* | 2.2315* | 2.8863* | 2.2297* |

**Table 2b**: Lo's modified R/S statistic for gold futures daily returns, absolute returns, squared returns, absolute deviation and square mean deviation

| $q$ | $R_t$ | $\lvert R_t \rvert$ | $R_t^2$ | $\lvert R_t - \overline{R} \rvert$ | $(R_t - \overline{R})^2$ |
|---|---|---|---|---|---|
| 0 | 2.1112* | 12.7156* | 9.1959* | 12.7059* | 9.1844* |
| 2 | 2.1218* | 10.2027* | 7.2954* | 10.1941* | 7.2879* |
| 5 | 2.1259* | 8.2787* | 5.9884* | 8.2726* | 5.9823* |
| 10 | 2.1551* | 6.6768* | 4.9009* | 6.6735* | 4.8970* |
| 25 | 2.0895* | 4.8066* | 3.7400* | 4.8046* | 3.7378* |
| 50 | 2.0890* | 3.6501* | 2.9690* | 3.6491* | 2.9675* |
| 100 | 2.1478* | 2.7462* | 2.3021* | 2.7457* | 2.3016* |

Note: * indicates significance at the 5% level. The critical interval is [0.809, 1.862].

**Table 3a**: Estimates for FIGARCH (1, d, 1) model for spot gold daily returns and volatility using Quasi Maximum Likelihood Estimation (QMLE)

| | $R_t$ | $\lvert R_t \rvert$ | $R_t^2$ | $\lvert R_t - \overline{R} \rvert$ | $(R_t - \overline{R})^2$ |
|---|---|---|---|---|---|
| d | 0.3370<br>(18.953) | 0.2842<br>(16.615) | 0.4115<br>(124.59) | 0.2834<br>(16.749) | 0.3548<br>(141.32) |
| Skewness | -0.0156 | 2.1376 | 9.8233 | 2.1572 | 9.8692 |
| Kurtosis | 4.7555 | 9.6744 | 161.41 | 9.7934 | 161.24 |
| Ljung-Box | 31.373 | 2726.81 | 370.05 | 2707.72 | 472.98 |

**Table 3b**: Estimates for FIGARCH (1, d, 1) models for gold futures daily returns and volatility using Quasi Maximum Likelihood Estimation (QMLE)

| | $R_t$ | $\lvert R_t \rvert$ | $R_t^2$ | $\lvert R_t - \overline{R} \rvert$ | $(R_t - \overline{R})^2$ |
|---|---|---|---|---|---|
| d | 0.3124<br>(18.287) | 0.2934<br>(14.616) | 0.3575<br>(51.671) | 0.2902<br>(14.077) | 0.3485<br>(93.757) |
| Skewness | -0.0197 | 2.1713 | 10.094 | 2.1960 | 10.354 |
| Kurtosis | 6.1205 | 10.129 | 165.66 | 10.335 | 165.39 |
| Ljung-Box | 16.053 | 2548.59 | 469.86 | 2535.78 | 478.15 |

Note: The values in parentheses are asymptotic t-statistics for the null hypothesis d=0. The sample skewness and Kurtosis are reported. Ljung-Box portmanteau test for up to 20th-order serial correlation in standardized residual is also reported.

**Table 4a**: Lo's modified R/S statistic for weekly returns, absolute returns and squared returns

| | Modified R/S statistic | | | | | |
|---|---|---|---|---|---|---|
| | $R_t$ | | $\lvert R_t \rvert$ | | $R_t^{\ 2}$ | |
| $q$ | Spot | Futures | Spot | Futures | Spot | Futures |
| 0 | 2.2023* | 1.9497* | 6.4238* | 6.2763* | 4.2289* | 4.0997* |
| 2 | 2.3251* | 2.0765* | 5.0335* | 4.9691* | 3.2890* | 3.2323* |
| 5 | 2.2907* | 2.0537* | 4.1034* | 4.0660* | 2.7908* | 2.7929* |
| 10 | 2.3381* | 2.0898* | 3.3467* | 3.3009* | 2.3519* | 2.3760* |

**Table 4b**: Lo's modified R/S statistic for monthly returns, absolute returns and squared returns

| | Modified R/S statistic | | | | | |
|---|---|---|---|---|---|---|
| | $R_t$ | | $\lvert R_t \rvert$ | | $R_t^{\ 2}$ | |
| $q$ | Spot | Futures | Spot | Futures | Spot | Futures |
| 0 | 1.9345* | 1.8571 | 3.4788* | 3.5537* | 2.7004* | 2.9897* |
| 2 | 2.0483* | 1.9447* | 2.9537* | 2.9342* | 2.3249* | 2.4897* |
| 5 | 1.9876* | 1.8698* | 2.4494* | 2.4045* | 2.0150* | 2.1152* |
| 10 | 1.8351 | 1.7281 | 2.0628* | 2.0152* | 1.7866 | 1.8497 |

Note: $R_t$ , $\lvert R_t \rvert$ , $R_t^{\ 2}$ represent gold monthly returns, absolute returns, squared returns respectively. * indicates significance at the 5% level. The critical interval is [0.809, 1.862].

**Table 5a**: The modified R/S statistic for forward rolling spot gold daily returns, daily absolute returns and daily square mean deviation

Daily returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Aug 2, 1976-Aug 2, 1983 | 1.7791 | 1.8587 | 1.8512 | 1.8640 | 1.7506 | 1.7174 | 1.7956 |
| Aug 2, 1976-Aug 2, 1988 | 1.8679* | 1.9492* | 1.9443* | 1.9605* | 1.8499 | 1.8173 | 1.8845* |
| Aug 2, 1976-Aug 2, 1993 | 2.0221* | 2.1029* | 2.0993* | 2.1105* | 1.9975* | 1.9571* | 2.0102* |
| Aug 2, 1976-Aug 2, 1998 | 1.9830* | 2.0544* | 2.0502* | 2.0606* | 1.9543* | 1.9198* | 1.9751* |
| Aug 2, 1976-Aug 2, 2003 | 2.0189* | 2.0801* | 2.0634* | 2.0661* | 1.9847* | 1.9714* | 2.0573* |
| Aug 2, 1976-Jul 14, 2008 | 2.3767* | 2.4310* | 2.4145* | 2.4176* | 2.3397* | 2.3454* | 2.4197* |

Daily absolute returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Aug 2, 1976-Aug 2, 1983 | 6.1339* | 5.0231* | 4.0849* | 3.3357* | 2.5279* | 2.0472* | 1.6115 |
| Aug 2, 1976-Aug 2, 1988 | 8.9926* | 7.2641* | 5.8814* | 4.7645* | 3.5181* | 2.7672* | 2.1260* |
| Aug 2, 1976-Aug 2, 1993 | 10.923* | 8.7196* | 7.0069* | 5.6275* | 4.0835* | 3.1571* | 2.3886* |
| Aug 2, 1976-Aug 2, 1998 | 12.484* | 9.8150* | 7.8163* | 6.2332* | 4.4689* | 3.4171* | 2.5602* |
| Aug 2, 1976-Aug 2, 2003 | 12.734* | 10.023* | 8.0212* | 6.4332* | 4.6432* | 3.5597* | 2.6734* |
| Aug 2, 1976- Jul 14, 2008 | 13.330* | 10.656* | 8.6039* | 6.9303* | 5.0081* | 3.8405* | 2.8890* |

Daily square mean deviation

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Aug 2, 1976-Aug 2, 1983 | 3.9163* | 3.4004* | 2.8485* | 2.3891* | 1.8563 | 1.5708 | 1.2730 |
| Aug 2, 1976-Aug 2, 1988 | 5.8204* | 5.0026* | 4.1660* | 3.4689* | 2.6527* | 2.1958* | 1.7426 |
| Aug 2, 1976-Aug 2, 1993 | 6.7920* | 5.8106* | 4.8248* | 4.0027* | 3.0361* | 2.4854* | 1.9518* |
| Aug 2, 1976-Aug 2, 1998 | 7.6228* | 6.4825* | 5.3611* | 4.4307* | 3.3386* | 2.7115* | 2.1142* |
| Aug 2, 1976-Aug 2, 2003 | 7.8043* | 6.6110* | 5.4777* | 4.5379* | 3.4299* | 2.7869* | 2.1737* |
| Aug 2, 1976- Jul 14, 2008 | 7.9606* | 6.7643* | 5.6171* | 4.6588* | 3.5210* | 2.8587* | 2.2297* |

**Table 5b**: Lo's modified R/S statistic for forward rolling gold futures daily returns, daily absolute returns and daily square mean deviation

Daily returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jan 2, 1979-Jan 2, 1988 | 1.8389 | 1.8345 | 1.8451 | 1.8819 | 1.7691 | 1.7200 | 1.7646 |
| Jan 2, 1979-Jan 2, 1993 | 1.4935 | 1.4949 | 1.5058 | 1.5329 | 1.4494 | 1.4145 | 1.4537 |
| Jan 2, 1979-Jan 2, 1998 | 1.4590 | 1.4648 | 1.4757 | 1.5015 | 1.4215 | 1.3883 | 1.4252 |
| Jan 2, 1979-Jan 2, 2003 | 1.6313 | 1.6368 | 1.6428 | 1.6664 | 1.6060 | 1.5871 | 1.6457 |
| Jan 2, 1979- Jul 14, 2008 | 2.1112* | 2.1218* | 2.1259* | 2.1551* | 2.0895* | 2.0890* | 2.1478* |

Daily absolute returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jan 2, 1979-Jan 2, 1988 | 8.2019* | 6.5344* | 5.3228* | 4.3285* | 3.2021* | 2.4910* | 1.9277* |
| Jan 2, 1979-Jan 2, 1993 | 10.5458* | 8.3034* | 6.6934* | 5.3801* | 3.8832* | 2.9617* | 2.2419* |
| Jan 2, 1979-Jan 2, 1998 | 12.1080* | 9.3953* | 7.4904* | 5.9691* | 4.2516* | 3.2078* | 2.3999* |
| Jan 2, 1979-Jan 2, 2003 | 12.2836* | 9.6288* | 7.7255* | 6.1977* | 4.4503* | 3.3736* | 2.5321* |
| Jan 2, 1979- Jul 14, 2008 | 12.7156* | 10.2027* | 8.2787* | 6.6768* | 4.8066* | 3.6501* | 2.7462* |

Daily square mean deviation

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jan 2, 1979-Jan 2, 1988 | 6.2731* | 4.8892* | 3.9963* | 3.2662* | 2.5442* | 2.0653* | 1.6409 |
| Jan 2, 1979-Jan 2, 1993 | 7.9280* | 6.1863* | 5.0434* | 4.1063* | 3.1478* | 2.5150* | 1.9640* |
| Jan 2, 1979-Jan 2, 1998 | 8.9140* | 6.9233* | 5.6195* | 4.5575* | 3.4594* | 2.7380* | 2.1176* |
| Jan 2, 1979-Jan 2, 2003 | 8.9492* | 7.0145* | 5.7285* | 4.6746* | 3.5681* | 2.8325* | 2.1943* |
| Jan 2, 1979- Jul 14, 2008 | 9.1844* | 7.2879* | 5.9823* | 4.8970* | 3.7378* | 2.9675* | 2.3016* |

Note: The critical interval is [0.809, 1.862]. * indicates significance at the 5% level.

**Table 6a**: The modified R/S statistic for backward rolling spot gold daily returns, daily absolute returns and daily square mean deviation

Daily returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jul 14, 2001- Jul 14, 2008 | 0.8703 | 0.8776 | 0.9101 | 0.8776 | 0.9101 | 1.0217 | 1.1099 |
| Jul 14, 1996- Jul 14, 2008 | 1.5732 | 1.5581 | 1.5228 | 1.5022 | 1.5506 | 1.6657 | 1.7050 |
| Jul 14, 1991- Jul 14, 2008 | 1.7164 | 1.7025 | 1.6690 | 1.6492 | 1.6868 | 1.8025 | 1.8582 |
| Jul 14, 1986- Jul 14, 2008 | 1.9506* | 1.9534* | 1.9259* | 1.9105* | 1.9201* | 2.0093* | 2.1048* |
| Jul 14, 1981- Jul 14, 2008 | 10.1533* | 8.5270* | 7.2007* | 5.9780* | 4.3881* | 3.3719* | 2.5778* |
| Aug 2, 1976- Jul 14, 2008 | 13.3309* | 10.6562* | 8.6039* | 6.9303* | 5.0081* | 3.8405* | 2.8890* |

Daily absolute returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jul 14, 2001- Jul 14, 2008 | 4.4326* | 4.0761* | 3.6801* | 3.2040* | 2.4244* | 1.8971* | 1.4935 |
| Jul 14, 1996- Jul 14, 2008 | 5.6613* | 4.8811* | 4.2398* | 3.6419* | 2.7932* | 2.2050* | 1.7318 |
| Jul 14, 1991- Jul 14, 2008 | 8.0597* | 6.8292* | 5.8304* | 4.9184* | 3.6750* | 2.8361* | 2.1701* |
| Jul 14, 1986- Jul 14, 2008 | 8.2294* | 7.1508* | 6.2095* | 5.2915* | 4.0106* | 3.1284* | 2.4163* |
| Jul 14, 1981- Jul 14, 2008 | 10.1533* | 8.5270* | 7.2007* | 5.9780* | 4.3881* | 3.3719* | 2.5778* |
| Aug 2, 1976- Jul 14, 2008 | 13.3309* | 10.6562* | 8.6039* | 6.9303* | 5.0081* | 3.8405* | 2.8890* |

Daily square mean deviation

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jul 14, 2001- Jul 14, 2008 | 3.9410* | 3.6928* | 3.3732* | 3.0094* | 2.3340* | 1.8608 | 1.4813 |
| Jul 14, 1996- Jul 14, 2008 | 3.9082* | 3.3312* | 2.9834* | 2.6763* | 2.2160* | 1.8444 | 1.5070 |
| Jul 14, 1991- Jul 14, 2008 | 5.5499* | 4.6991* | 4.1697* | 3.6963* | 2.9968* | 2.4432* | 1.9493* |
| Jul 14, 1986- Jul 14, 2008 | 5.2865* | 4.6613* | 4.2271* | 3.8031* | 3.1382* | 2.5873* | 2.0878* |
| Jul 14, 1981- Jul 14, 2008 | 6.8248* | 6.0257* | 5.3067* | 4.5968* | 3.5773* | 2.8653* | 2.2844* |
| Aug 2, 1976- Jul 14, 2008 | 7.9606* | 6.7643* | 5.6171* | 4.6588* | 3.5210* | 2.8587* | 2.2297* |

**Table 6b**: Lo's modified R/S statistic for backward rolling gold futures daily returns, daily absolute returns and daily square mean deviation

Daily returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jul 14, 1999- Jul 14, 2008 | 1.1492 | 1.1615 | 1.1435 | 1.1508 | 1.2113 | 1.3568 | 1.4710 |
| Jul 14, 1994- Jul 14, 2008 | 1.5924 | 1.5924 | 1.5891 | 1.5939 | 1.6483 | 1.7705 | 1.8075 |
| Jul 14, 1989- Jul 14, 2008 | 1.6586 | 1.6860 | 1.6789 | 1.6853 | 1.7295 | 1.8343 | 1.9071* |
| Jul 14, 1984- Jul 14, 2008 | 1.6825 | 1.7328 | 1.7457 | 1.7587 | 1.7915 | 1.8858* | 1.9842* |
| Jan 2, 1979- Jul 14, 2008 | 2.1112* | 2.1218* | 2.1259* | 2.1551* | 2.1551* | 2.0890* | 2.1478* |

Daily absolute returns

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jul 14, 1999- Jul 14, 2008 | 4.2331* | 3.9002* | 3.4929* | 3.0656* | 2.4271* | 1.9866* | 1.6074 |
| Jul 14, 1994- Jul 14, 2008 | 6.8926* | 6.0741* | 5.2260* | 4.4056* | 3.2890* | 2.5600* | 1.9685* |
| Jul 14, 1989- Jul 14, 2008 | 7.7901* | 7.1170* | 6.1855* | 5.2486* | 3.9438* | 3.0683* | 2.3675* |
| Jul 14, 1984- Jul 14, 2008 | 7.8063* | 7.0269* | 6.1871* | 5.3064* | 4.0306* | 3.1766* | 2.4945* |
| Jan 2, 1979- Jul 14, 2008 | 12.7165* | 10.2027* | 8.2787* | 6.6768* | 4.8066* | 3.6501* | 2.7462* |

Daily square mean deviation

| Sample Period | q=0 | q=2 | q=5 | q=10 | q=25 | q=50 | q=100 |
|---|---|---|---|---|---|---|---|
| Jul 14, 1999- Jul 14, 2008 | 3.3723* | 3.1098* | 2.8486* | 2.6234* | 2.2518* | 1.9702* | 1.7024 |
| Jul 14, 1994- Jul 14, 2008 | 4.1239* | 3.7529* | 3.3872* | 3.0533* | 2.5135* | 2.1022* | 1.7229 |
| Jul 14, 1989- Jul 14, 2008 | 4.8404* | 4.4908* | 4.1142* | 3.7457* | 3.1163* | 2.6113* | 2.1476* |
| Jul 14, 1984- Jul 14, 2008 | 4.8462* | 4.5054* | 4.1571* | 3.8042* | 3.1706* | 2.6799* | 2.2351* |
| Jan 2, 1979- Jul 14, 2008 | 9.1844* | 7.2879* | 5.9823* | 4.8970* | 3.7378* | 2.9675* | 2.3016* |

Note: The critical interval is [0.809, 1.862]. * indicates significance at the 5% level.

**Table 7a**: Estimates for FIGARCH (1, d, 1) model for spot gold daily returns and volatility for three subsamples using Quasi Maximum Likelihood Estimation (QMLE)

**Structural break in 1979**

| Period | August 2, 1976-February 11, 1979 | | February 12, 1979-July 14, 2008 | |
|---|---|---|---|---|
| Series | $R_t$ | $\left(R_t - \overline{R}\right)^2$ | $R_t$ | $\left(R_t - \overline{R}\right)^2$ |
| d | 0.2155<br>(2.8546) | 0.4445<br>(60.600) | 0.3408<br>(18.457) | 0.47928<br>(46.580) |
| Skewness | 0.7019 | 7.4929 | -0.0830 | 10.295 |
| Kurtosis | 4.8170 | 86.795 | 4.6875 | 174.84 |
| Ljung-Box | 21.038 | 31.842 | 30.550 | 295.00 |

**Structural break in 1987**

| Period | August 2, 1976-August 9, 1987 | | August 10, 1987-July 14, 2008 | |
|---|---|---|---|---|
| Series | $R_t$ | $\left(R_t - \overline{R}\right)^2$ | $R_t$ | $\left(R_t - \overline{R}\right)^2$ |
| d | 0.3094<br>(8.9713) | 0.6116<br>(18.303) | 0.3287<br>(14.918) | 0.3141<br>(24.935) |
| Skewness | -0.0052 | 7.5271 | -0.0512 | 10.934 |
| Kurtosis | 3.7569 | 94.138 | 5.0103 | 192.46 |
| Ljung-Box | 33.577 | 161.51 | 30.952 | 146.20 |

**Structural break in 2007**

| Period | August 2, 1976-July 1, 2007 | | July 2, 2007-July 14, 2008 | |
|---|---|---|---|---|
| Series | $R_t$ | $\left(R_t - \overline{R}\right)^2$ | $R_t$ | $\left(R_t - \overline{R}\right)^2$ |
| d | 0.3285<br>(18.284) | 0.3592<br>(178.70) | 0.2103<br>(2.0487) | 0.3968<br>(1.1E+08) |
| Skewness | 0.0142 | 9.6526 | -0.9355 | 7.3657 |
| Kurtosis | 4.8010 | 158.61 | 3.5391 | 76.661 |
| Ljung-Box | 31.289 | 438.80 | 19.176 | 21.050 |

**Table 7b**: Estimates for FIGARCH (1, d, 1) models for gold futures daily returns and volatility for three subsamples using Quasi Maximum Likelihood Estimation (QMLE)

**Structural break in 1979**

| Period | January 2, 1979-February 11, 1979 | | February 12, 1979-July 14, 2008 | |
|---|---|---|---|---|
| Series | $R_t$ | $\left(R_t - \overline{R}\right)^2$ | $R_t$ | $\left(R_t - \overline{R}\right)^2$ |
| d | 0.0000<br>(0.0000) | 1.0000<br>(105.58) | 0.3111<br>(17.991) | 0.3495<br>(32.487) |
| Skewness | 0.1282 | 1.2182 | -0.0246 | 10.101 |
| Kurtosis | -0.1905 | 0.6149 | 6.1522 | 166.18 |
| Ljung-Box | 33.414 | 11.573 | 15.728 | 474.10 |

**Structural break in 1987**

| Period | January 2, 1979-August 9, 1987 | | August 10, 1987-July 14, 2008 | |
|---|---|---|---|---|
| Series | $R_t$ | $\left(R_t - \overline{R}\right)^2$ | $R_t$ | $\left(R_t - \overline{R}\right)^2$ |
| d | 0.2459<br>(8.7148) | 0.4637<br>(25.777) | 0.3129<br>(14.436) | 0.3112<br>(22.453) |
| Skewness | 0.0862 | 3.7375 | -0.0951 | 12.078 |
| Kurtosis | 1.9679 | 20.785 | 7.5902 | 208.06 |
| Ljung-Box | 26.521 | 325.75 | 14.500 | 130.69 |

**Structural break in 2007**

| Period | January 2, 1979-July 1, 2007 | | July 2, 2007-July 14, 2008 | |
|---|---|---|---|---|
| Series | $R_t$ | $\left(R_t - \overline{R}\right)^2$ | $R_t$ | $\left(R_t - \overline{R}\right)^2$ |
| d | 0.3077<br>(18.016) | 0.4061<br>(48.112) | 0.0381<br>(0.6039) | 1.0000<br>(313.59) |
| Skewness | 0.0215 | 10.275 | -0.7925 | 6.3415 |
| Kurtosis | 6.2455 | 174.11 | 2.4652 | 61.637 |
| Ljung-Box | 12.413 | 427.42 | 31.531 | 16.867 |

Note: The values in parentheses are asymptotic t-statistics for the null hypothesis d=0.