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Exchange-Rate Return Predictability and the Adaptive Markets Hypothesis: Evidence from Major Foreign Exchange Rates

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Abstract

This study examines return predictability of major foreign exchange rates by testing for martingale difference hypothesis (MDH) using daily and weekly nominal exchange rates from 1975 to 2009. We use alternative MDH tests for linear and nonlinear dependence, which include wild bootstrap automatic variance ratio test, generalized spectral test, and consistent tests. We evaluate time-varying return predictability by applying these tests with fixed-length moving sub-sample windows of two years. While exchange rate returns are found to be unpredictable most of times, we do observe episodes of statistically significant return predictability. They are associated with coordinated central bank interventions and the subprime mortgage crisis in 2007. This finding suggests that return predictability of foreign exchange rates occurs from time to time depending on changing market conditions, which is consistent with the implications of the adaptive markets hypothesis.

Keywords: Adaptive markets hypothesis; martingale difference hypothesis; variance ratio test; spectral test.

JEL Classification: G14; G15; C12; C14.

1 Introduction

One of the earliest and most enduring questions in economics and finance is whether the prices are predictable. Since the seminal papers of Samuelson (1965) and Fama (1965), the efficient market hypothesis (EMH thereafter) states that efficient market prices follow a random walk or a martingale[1], and always fully and instantaneously reflect all available and relevant information, where the information set consists of past prices and returns. As a result, future prices are purely unpredictable based on past price information and fluctuate only in response to the random flow of news (Fama, 1970, 1991). Moreover, since price adjustment to a new piece of information is instantaneous and accurate, returns cannot be predicted. Most of the EMH studies on financial markets have tested for the weak-form through the martingale difference hypothesis (MDH thereafter)[2], where the current price is the best predictor of the future price and the returns are independent (or uncorrelated) with the past values. If the nominal exchange rate follows a martingale difference sequence (MDS thereafter), then the market is weak-form efficient, and hence not predictable. This means that it is impossible for an exchange trader to gain excess returns over time through speculation. Alternatively, if the nominal exchange rate is predictable, then the market is not weak-form efficient. This means that the exchange traders can generate abnormal returns through speculation. For these reasons, the predictability of return has been an important issue to this concerned with market efficiency.

There might be several alternatives explanations for predictability (not EMH) in exchange rate markets: (i) the prices in these markets do not quickly adjust to the new information (Fama, 1970; Melvin, 2004); (ii) the exchange rates are not set at the equilibrium level due to distortions in the pricing of capital and the valuing of risk (Smith et al., 2002); (iii) the emergence of a parallel/ black market due to the existence of the exchange rate controls and resulting divergence between the equilibrium rate and the official rate (Diamandis et al., 2007); (iv) the exchange rate regime is also a major determinant of foreign exchange market efficiency. If the regulatory agencies do not allow the foreign banks the free access to the foreign exchange markets and products, the foreign exchange market may not be efficient; (v) the overshooting or undershooting phenomenon of exchange rates (Liu and He, 1991); and (vi) the central

[1]The terms "random walk" and "martingale" have been interchangeably used in the literature. However, strictly speaking, the innovations series is *i.i.d.* for "random walk", while it is a martingale difference sequence for "martingale". See Escanciano and Lobato (2009b) for a discussion.

[2]See Lo and MacKinlay (2001) for a discussion on MDH and EMH.

bank intervention (Yilmaz, 2003; Beine et al., 2009).[3]

There have been numerous studies that tested MDH in major foreign exchange rates. Since Meese and Rogoff (1983) showed that the structural models of exchange rate determination had inferior performance than a MDS in out-of-sample forecasts, many studies strived to uncover the empirical regularities in exchange rate behavior. In the literature, several methods have been used for testing martingale behavior, including autocorrelation tests (Box and Pierce, 1970; Ljung and Box, 1978), variance ratio tests (Lo and MacKinlay, 1988, 1989) and spectral tests (Durlauf, 1991; Hong, 1996) and their improved modifications.[4] They have been used in many empirical applications on foreign exchange rates by Hsieh (1988), Liu and He (1991), Fong et al. (1997), Wright (2000), Lobato et al. (2001), Yilmaz (2003), Kuan and Lee (2004), Escanciano and Velasco (2006) and Escanciano and Lobato (2009a, 2009b), among others. However, the results are overall mixed and scattered over numerous studies that use different sample periods (often outdated), methods (often one type of methodology)[5] and data frequencies (weekly or daily). Recently, Lo (2004, 2005) proposed the concept of adaptive markets hypothesis (AMH) which is a new version of the EMH derived from evolutionary principles. The AMH gives a framework to reconcile the EMH with the notion of bounded rationality and helps understand the time-variation in the degree of market efficiency.[6] An important implication of the

[3]Note that no consensus has been reached on the effect of central banks intervention. For some, the impact of intervention vanishes after a few minutes or a day (Dominguez, 2006). For others, it lasts several days or weeks (Fratzscher, 2008). Both Yilmaz (2003) and Szakmary and Mathur (1997) document that exchange rates can deviate from the martingale property and produce profitable trading returns during times of coordinated central bank interventions. On the other hand, Neely (2002) provides evidence that central bank intervention does not generate technical trading profits. Furthermore, the European Central Bank has conduced only four interventions since 1999. The Fed has been even less active in the exchange rate market.

[4]See Escanciano and Lobato (2009b) for a discussion on testing the MDH.

[5]All these studies on the MDH examine foreign exchange rates only from one methodology, except Escanciano and Lobato (2009a, 2009b).

[6]The AMH is developed by coupling the evolutionary principle with the notion of bounded rationality (Simon, 1955). A bounded rational investor is said to exhibit satisfying rather than optimal behavior. Optimization can be costly and market participants with limited access to information or abilities to process information are merely engaged in attaining a satisfactory outcome. Lo (2004, 2005) argues that a satisfactory outcome is attained not analytically, but through an evolutionary process involving trial error and natural selection. The process of natural selection ensures the survival of the fittest and determines the number and composition of market participants. Market participants adapt to constantly changing environment and rely on heuristics to make investment choices (Kim et al., 2009). Based on the evolutionary perspective, profit opportunities do exist from time to time. Though they disappear after being exploited by investors, new opportunities are continually being created as groups of market

AMH is that return predictability may arise time to time due to changing business conditions (cycles, bubbles, crashes, ...) and institutions.

Moreover, many exchange rate markets frequently experience structural changes or outliers, due to exceptional and unexpected events such as financial crisis and changes in regime. These events have strong implications for the psychology of market participants and the way they incorporate new information to prices, which in turn may generate time variation in serial correlation in returns. In view of Lo's (2004, 2005) AMH, it is highly likely that the degree of return predictability is driven largely by such dynamic market conditions. To the best of our knowledge, Yilmaz (2003) and Chuluun et al. (2011) are the only studies that evaluate the MDH from time-varying measures in foreign exchange rates, but without link with the AMH.[7]

The aim of this paper is to evaluate the evolution of return predictability of the major foreign exchange rates and to examine whether its evolution is consistent with the AMH. This study is based on an extensive sample of daily and weekly data for major foreign exchange rates over the period 1974–2009 in order to take into account the subprime mortage crisis in 2007. We measure the degree of return predictability using three alternative MDS tests, namely the wild bootstrap automatic variance-ratio test of Kim (2009), the generalized spectral shape test of Escansiano and Velasco (2006), and the consistent tests of Dominguez and Lobato (2003). These tests are robust to non-normality and conditional heteroscedasticity which are present in foreign exchange rates as well as the presence of linear or nonlinear dependence. They are applied by using a moving sub-sample window in order to obtain inferential outcomes robust to possible structural changes or influential outliers.

The remainder of this paper is organized as follows: Section 2 presents the alternative martingale tests; Section 3 summarizes the characteristics of the data and reports the empirical results. The conclusion is drawn in Section 4.

2 Tests for Martingale Difference Hypothesis

2.1 Brief Literature Survey

In empirical testing for market efficiency or return predictability, the variance ratio (VR thereafter) test has been widely used. Since Lo and MacKinlay (1988) propose its

participants, institutions and business conditions change. See Lim and Brooks (2010) for a survey on the AMH.

[7]See Lim and Brooks (2010) for a review on the studies using time-varying tests in stock returns series.

original version, the test has undergone a number significant improvements, including the multiple variance ratio test of Chow and Denning (1993), sign and rank tests of Wright (2000), and wild bootstrap test of Kim (2006).[8] The test is based on the property that, if return is purely random, the variance of k-period return is k times the variance of the one-period return. Hence, the variance ratio $VR(k)$, defined as the ratio of $1/k$ times the variance of k-period return to that of one-period return, should be equal to one for all values of k. To implement the test, one should test for the null hypothesis that the VR is equal to one for a set of (holding periods) k values. For example, popular choices in empirical applications include $k \in \{2,5,10,30\}$ for daily return, while $k \in \{2,4,8,16\}$ for weekly return (see, for example, Belaire-Franch and Opong, 2005; and Fong et al., 1997). However, these choices are entirely arbitrary and adopted without any concrete statistical justifications. In view of this, Choi (1999) propose an automatic variance ratio (AVR thereafter) test, in which the optimal value of holding period k is determined automatically using a completely data-dependent procedure. In a recent study, Kim (2009) evaluates Choi's (1999) test under conditional heteroskedasticity and has found that the test shows size distortion. Kim (2009) proposes wild bootstrapping of the test and find that it significantly improves the size and power properties of the test. In addition, this wild bootstrap AVR test compares favorably to the other alternatives such as the wild bootstrap Chow-Denning test of Kim (2006), the power-transformed test of Chen and Deo (2006) and the joint sign test of Kim and Shamsuddin (2008), where the choice of holding periods is arbitrarily made.

An alternative test for return predictability based on serial correlation of return is the portmanteau test of Box and Pierce (1970) and Ljung and Box (1978). Although a few early papers on testing weak-form market efficiency adopt this test, it has been largely neglected in the market efficiency literature. This is mainly because of the well-known fact that the Box-Pierce and Ljung-Box portmanteau tests suffer from low power. More importantly, it assumes that the returns are identically and independently distributed ($i.i.d$), which is a condition hardly justifiable for financial returns where the existence of conditional heteroscedasticity is a stylized fact. Recently, a series of papers propose modified portmanteau tests which are applicable to return under more general conditions allowing for unconditional or conditional heteroscedasticity, which include Lobato et al. (2001, 2002) and Escanciano and Lobato (2009a). In particular, Escanciano and Lobato (2009a) propose an automatic portmanteau test in which the optimal lag order is selected using a fully data dependent procedure. Escanciano

[8] See Hoque et al. (2007) and Charles and Darné (2009) for a review on the VR tests.

and Lobato (2009a) report that their automatic test shows desirable small sample properties such as correct size and high power, under the presence of conditional heteroscedasticity, and it is more powerful than the robustified tests of Lobato et al. (2001, 2002), where the choice of lag order is arbitrarily made. Another approach to test serial correlation has been introduced by Andrews and Ploberger (1996) which is designed for the case where the time series is generated by ARMA (1,1) models under the alternative. Recently, Nankervis and Savin (2010) generalize the Andrews-Ploberger tests when the time series is serially uncorrelated but statistically dependent, in the same approach used by Lobato et al. (2002) to generalize the Box-Pierce tests. They find that their generalized Andrews-Ploberger tests have good power properties for nonseasonal alternatives compared to the generalized Box-Pierce tests and the Deo (2000) tests.

The above-mentioned tests are (linear) autocorrelation-based tests, which can capture only the linear dependence of return on its own past. However, the returns can show non-linear dependence, and the autocorrelation-based tests may not be capable of detecting such dependence structure. Given the evidence of non-linear dependence in returns, evaluation of linear dependence only may be restrictive. The generalized spectral shape test of Escanciano and Velasco (2006) is a means of detecting possible non-linear dependence in returns. This test can capture a wide range of linear and non-linear dependence in mean, allowing for a general form of unknown conditional heteroscedasticity in variance. According to the Monte Carlo experiment of Escansiano and Velasco (2006), the test is more powerful than its competitors such as Deo (2000), Domínguez and Lobato (2003), Kuan and Lee (2003) and Hong and Lee (2003, 2005).[9]

Recently, Charles et al. (2010) showed from Monte Carlo experiments that the wild bootstrap AVR test of Kim (2009), the generalized spectral shape test of Escansiano and Velasco (2006) (GSS thereafter) and the consistent test of Domínguez and Lobato (2003) (DL thereafter) give higher power against a wide range of linear and non-linear models, with no size distortion, than the automatic portmanteau test of Escanciano and Lobato (2009a). More precisely, the AVR test shows the highest power against linear dependence; while the GSS and DL tests perform most desirably under nonlinear dependence.

[9]The generalized spectral tests (Hong and Lee, 2003, 2005; Escansiano and Velasco, 2006) have the additional property of being able to identify non-linear dependencies as regards to the linear spectral tests, such as those of Durlauf (1991) and Deo (2000) which are robust to various forms of unconditional and conditional heteroscedasticity, respectively.

In this section, we present the details of the wild bootstrap AVR test of Kim (2009), the generalized spectral shape test of Escansiano and Velasco (2006), and the consistent tests of Dominguez and Lobato (2003).

2.2 Test based on linear measures of dependence

Let Y_t denote asset return at time t, where $t = 1, ..., T$. Choi's (1999) AVR test is based on a variance ratio estimator related to the normalized spectral density estimator at zero frequency. Namely,

$$\widehat{VR}(k) = 1 + 2\sum_{i=1}^{T-1} k(i/k)\widehat{\rho}(i), \tag{1}$$

where $\hat{\rho}(i) = \hat{\gamma}(i)/\hat{\gamma}(0)$ is the sample autocorrelation of order i, $\hat{\gamma}(i)$ is the sample autocovariance of order i, and

$$k(x) = \frac{25}{12\pi^2 x^2}\left[\frac{\sin(6\pi x/5)}{6\pi x/5} - \cos(6\pi x/5)\right],$$

is the quadratic spectral kernel. According to Choi (1999), under the condition that Y_t is an $i.i.d.$ sequence with finite fourth moment,

$$AVR(k) = \sqrt{T/k}[\widehat{VR}(k) - 1]/\sqrt{2} \rightarrow_d \mathbf{N}(0,1), \tag{2}$$

as $T \rightarrow \infty$, $k \rightarrow \infty$, and $T/k \rightarrow \infty$. To test for $H_0 : VR(k) = 1$, a choice for the value of lag truncation point k should be made, which is equivalent to the value of holding period in the time domain. Choi (1999) proposes a data-dependent method of choosing k optimally, following Andrews (1991), noting that this choice may exert an enormous impact on the variance ratio test. The AVR test statistic with the optimally chosen lag truncation point is denoted as $AVR(k^*)$; Choi (1991) notes that k^* chosen by Andrews' (1991) method satisfies the conditions related to (2).

Kim's (2009) wild bootstrap AVR test is conducted in three stages as follows:

1. Form a bootstrap sample of size T as $Y_t^* = \eta_t Y_t$ $(t = 1, ..., T)$ where η_t is a random variable with zero mean and unit variance;

2. Calculate $AVR^*(k^*)$, the $AVR(k^*)$ statistic calculated from $\{Y_t^*\}_{t=1}^T$;

3. Repeat 1 and 2 B times, to produce the bootstrap distribution of the AVR statistic $\{AVR^*(k^*; j)\}_{j=1}^B$.

The test for H_0 against the two-tailed alternative is conducted to using the p-value, which is estimated as the proportion of the absolute values of $\{AVR^*(k^*;j)\}_{j=1}^B$ greater than the observed statistic $AVR(k^*)$. Alternatively, one may use the $100(1-2\alpha)$ per cent confidence interval $[AVR^*(\alpha), AVR^*(1-\alpha)]$, where $AVR^*(\alpha)$ denotes the α^{th} percentile of $\{AVR^*(k^*;j)\}_{j=1}^B$.

2.3 Tests based on nonlinear measures of dependence

Suppose Y_t follows a martingale difference sequence, and the null hypothesis of interest is $H_0 : E(Y_t|Y_{t-1}, Y_{t-2}, ...) = \mu$, where μ is a real number. Escansiano and Velasco (2006) express the above null hypothesis in a form of pairwise regression function. That is, $H_0 : m_j(y) = 0$, where $m_j(y) = E(Y_t - \mu|Y_{t-j} = y)$, against $H_1 : P[m_j(y) \neq 0] > 0$ for some j. Following Bierens (1982), Escansiano and Velasco (2006) note that the above null hypothesis is equivalent to the following condition:

$$\gamma_j(x) \equiv E[(Y_t - \mu)e^{ixY_{t-j}}] = 0,$$

where $\gamma_j(x)$ represents an autocovariance measure in a non-linear framework and x represents any real number. Escansiano and Velasco (2006) propose the use of the generalized spectral distribution function

$$H(\lambda, x) = \gamma_0(x)\lambda + 2\sum_{j=1}^{\infty} \gamma_j(x)\frac{\sin(j\pi\lambda)}{j\pi},$$

where λ is any real number in [0,1]. The sample estimate of the above distribution function is written as

$$\widehat{H} = \widehat{\gamma}_0(x)\lambda + 2\sum_{j=1}^{\infty}(1 - \frac{j}{T})\widehat{\gamma}_j(x)\frac{\sin(j\pi\lambda)}{j\pi},$$

where $\widehat{\gamma}_j(x) = (T-j)^{-1}\sum_{t=1+j}^{T}(Y_t - \overline{Y}_{T-j})e^{ixY_{t-j}}$ and $\overline{Y}_{T-j} = (T-j)^{-1}\sum_{t=1+j}^{T} Y_t$. Under the null hypothesis, the above generalized spectral distribution function has the value $\widehat{H}_0(\lambda, x) = \widehat{\gamma}_0(x)\lambda$, and the statistic of interest to test for H_0 is constructed as

$$\begin{aligned} S_T(\lambda, x) &= (0.5T)^{1/2}\{\widehat{H}(\lambda, x) - \widehat{H}_0(\lambda, x)\} \\ &= \sum_{j=1}^{T-1}(T-j)^{0.5}\widehat{\gamma}_j(x)\frac{\sqrt{2}\sin(j\pi x)}{j\pi}. \end{aligned}$$

To evaluate the value of S_T for all possible values of λ and x, Escansiano and Velasco (2006) use the Cramer-von Mises norm to yield the statistic of the form

$$D_T^2 = \int_R \int_0^1 |S_T(\lambda, x)^2| W(dx)d\lambda = \sum_{j=1}^{T-1}\frac{(T-j)}{(j\pi)^2}\int_R |\widehat{\gamma}_j(x)|^2 W(dx),$$

where $W()$ is a weighting function satisfying some mild conditions. Using the standard normal distribution as a weighting function, Escansiano and Velasco (2006) obtain the GSS test statistic

$$D_T^2 = \sum_{j=1}^{T-1} \frac{(T-j)}{(j\pi)^2} \sum_{t=j+1}^{T} \sum_{s=j+1}^{T} \exp(-0.5(Y_{t-j} - Y_{s-j})^2). \tag{3}$$

Dominguez and Lobato (2003) proposed alternative tests based on nonlinear measure of dependence, which test for no directional predictability. Their tests (hereafter called the DL tests), based on Cramer-von Mises (CvM) and Kolmogorov-Smirnov (KS) statistics, can be written as

$$\begin{aligned} CvM_{T,p} &= \frac{1}{\widehat{\sigma}^2 T^2} \sum_{j=1}^{T} [\sum_{t=1}^{T} (Y_t - \overline{Y}) 1(\widetilde{Y}_{t,p} \leq \widetilde{Y}_{j,p})]^2; \\ KS_{T,p} &= \max_{1 \leq i \leq T} |\frac{1}{\widehat{\sigma}\sqrt{T}} \sum_{t=1}^{T} (Y_t - \overline{Y}) 1(\widetilde{Y}_{t,p} \leq \widetilde{Y}_{j,p})|, \end{aligned} \tag{4}$$

where $\widetilde{Y}_{t,p} = (Y_{t-1}, ..., Y_{t-p})$ and p is a positive integer.

The GSS and DL test statistics given in (3) to (4) do not possess the standard asymptotic distributions. To implement the tests in finite samples, the above authors recommend the use of the wild bootstrap. That is, the p-value of the test can be obtained from the wild bootstrap distribution, as described for the AVR test. The DL tests are conditional on finite-dimensional information set, requiring the choice of lag order p; while the GSS exploits infinite-dimensional information set. As noted in Escanciano and Velasco (2006), the GSS test is only pairwise consistent, but is inconsistent against pairwise MDS which are non-MDS.

3 Empirical findings

3.1 Brief Literature Survey

There have been numerous studies that tested MDH in major foreign exchange rates. Since Meese and Rogoff (1983) showed that the structural models of exchange rate determination had inferior performance than a MDS in out-of-sample forecasts, many studies strived to uncover the empirical regularities in exchange rate behavior. However, the results are overall mixed and scattered over numerous studies that use different sample periods, methods and data frequencies. Table 1 presents a brief

summary of the selected studies, indicating the methodologies used, the types and frequencies of data employed, and the foreign exchange rates analyzed.[10]

Liu and He (1991), Fong et al. (1997), Wright (2000), Yilmaz (2003), Chang (2004), and Belaire-Franch and Opong (2005) investigate the MDH in major exchange rates from VR tests. Liu and He (1991) apply VR tests based on Lo and MacKinlay (1988) and provide evidence that the MDH is rejected for five major foreign exchange rates, namely Canadian dollar, French franc, German mark, Japanese yen, and British pound. Their results suggest that autocorrelations are present in weekly increments in nominal exchange rate series on the period 1974–1989. Fong et al. (1997), Wright (2000), Yilmaz (2003) and Chang (2004) re-examine the same five exchange rates using various VR tests. Wright (2000) and Yilmaz (2003)[11] apply non-parametric sign and rank-based VR tests and multiple Chow-Denning (1993) and Richardson-Smith (1991) VR tests and confirm the results obtained by Liu and He (1991). Fong et al. Ouliaris (1997) find that the Richardson-Smith test fails to reject MDH for all five currencies, whereas the Chow-Denning test continues to reject the hypothesis for the French franc, German mark, and Japanese yen.[12] Chang (2004) provides evidence rejecting the MDH for the Japanese yen, while the results for the other four currencies were inconclusive when employing the Lo-MacKinlay VR test with a bootstrap resampling technique and daily data. Belaire-Franch and Opong (2005) use nonparametric ranks and sign-based VR tests, suggested by Wright (2000), with size adjustment for multiple tests to examine the MDH of ten daily Euro-based nominal exchange rates (Australian dollar, Canadian dollar, New Zealand dollar, Japanese yen, British pound, Norwegian kroner, Singapore dollar, Swedish krona, Swiss franc, and United States dollar). Their results indicate that the behavior of Euro exchange rates for the major trading currencies is weak-form efficient.

Fong and Ouliaris (1995), Hong (1999), Hong and Lee (2003), Kuan and Lee (2004), and Escanciano and Velasco (2006) study foreign exchange rates from spectral tests. Fong and Ouliaris (1995) re-analyze the same five currencies of Liu and He (1991) for the same period and frequency from a family of the spectrum-based tests proposed by Durlauf (1991) and reject the MDH only for the British pound. Kuan

[10] See Azad (2009) for a survey on the different kinds of methodologies used to explain the MDH of the exchange rate markets.

[11] Yilmaz (2003) also examined daily data for the Swiss franc and Italian lira.

[12] The difference between the results obtained by Fong et al. (1997) and Yilmaz (2003), even if they employ the same VR tests, can be explained by the fact that Fong et al. (1997) investigate weekly data between October 1979, and March 1989, whereas Yilmaz (2003) studies daily data between January 2, 1974, and February 12, 2001

and Lee (2004) obtain the same results from their spectral test, except for the British currency for which they do not reject the MDH, whereas Hong and Lee (2003), Escanciano and Velasco (2006) and Escanciano and Lobato (2009b) reject the null hypothesis for all the currencies from generalized spectral tests.[13] This result is confirmed by Hong (1999) for the German mark on the period 1976–1995, using generalized spectral test.

Hsieh (1988), Lobato et al. (2001), Horowitz et al. (2006), Escanciano and Lobato (2009a, 2009b), and Chortareas et al. (2010) analyze the MDH for various major exchange rates from autocorrelation tests. Hsieh (1988) investigates the five major currencies from daily data on the 1974–1983 period and from heteroscedasticity-adjusted Box-Pierce test and rejected the null. Lobato et al. (2001) use a modified Box-Pierce test on daily returns for the German mark, Japanese yen, Swiss franc, and the British pound and find that the MDH is not rejected for all the currencies on the period 1976–1996. Escanciano and Lobato (2009a) obtain the same results for the Canadian dollar and the Japanese yen on the period 1987–2007 using their automatic portmanteau test, whereas they reject the MDH for the British pound.[14] Escanciano and Lobato (2009b) find that the Canadian, Japan and British currencies have no linear dependence on the period 2004–2007 from various autocorrelation tests. This result is confirmed by Horowitz et al. (2006) for the British currency on the period 1993–1996 from a bootstrapped Box-Pierce test. Chortareas et al. (2010) study the MDH for various OECD exchange rates from generalized Andrews-Ploberger autocorrelation tests proposed by Nankervis and Savin (2010). The tests do not reject the MDH for most exchange rates.

Finally, Yilmaz (2003) and Chuluun et al. (2011) are the only studies that evaluate the MDH from time-varying measures. More precisely, the VR tests of Chow-Denning (1993) and Richardson-Smith (1991) in Yilmaz (2003), and Lo and MacKinlay (1988) and Wrigth (2000) in Chuluun et al. (2011). They apply MDH tests to moving

[13]The difference between the results found by Fong and Ouliaris (1995), Kuan and Lee (2004), Escanciano and Velasco (2006) and Escanciano and Lobato (2009b) can be explained by the methods employed. Deo (2000) demonstrates that the Durlauf (1991) spectral test used by Fong and Ouliaris (1995) is not robust to conditional heteroskedasticity and may over-reject the MDH. Escansiano and Velasco (2006) show that their GSS test is more powerful than the test of Kuan and Lee (2003). Note that Hong and Lee (2003) use an extensive sample which covers the period 1975–1998 whereas Escanciano and Lobato (2009b) employ more recent data from 2004–2007 (only for Canada, Japan and UK).

[14]Note that Escanciano and Lobato (2009a) also use the modified Box-Pierce test of Lobato et al. (2001) on their sample size and find that the robustified Box-Pierce test do not reject the MDH for the British pound when the lag order $p = 20$. Escanciano and Lobato (2009a) show that their test is more powerful than that of Lobato et al. (2001).

subsample windows on the major exchange rates and twenty-nine floating exchanges rates, respectively.[15]

3.2 Data and Descriptive Statistics

The data of the study consists of the daily nominal exchange rates, traded five days per week, for the Australian dollar (AU$), British pound (GBP), Canadian dollar (CA$), Japanese yen (JPY), and Swiss franc (CHF) relative to the US dollar, which include all the important US dollar denominated exchange rates that are classified as independently floating by the International Monetary Fund. The data span from January 2, 1974, to July 17, 2009, namely 9,274 observations. For the weekly data, the prices are observed on Wednesday or on the next day if the markets are closed on Wednesday. The nominal exchange rate data are the daily noon buying rates in New York City certified by the Federal Reserve Bank of New York for customs and cable transfers purposes which are obtained from the Federal Reserve.[16] We use the both frequencies to see if the results are robust to different degree of data aggregation and time horizons. They overcome issues like biasness with daily data (e.g., non-trading, bid-ask spread, asynchronous prices, etc.) and assumptions with weekly data (alternate day price in the case of non-trading on the day of the week observed), especially for the developed markets.

We first present descriptive statistics for the return series calculated as the first differences in the logarithms of the nominal exchange rates for daily and weekly data in Table 2. For the daily data (Panel A), CA$ exhibits the best performance as well as the less volatile exchange rates, as the standard deviation shows. CHF displays the worst performance as well as the higher standard deviation. It can be also concluded that on average, US$ has depreciated against the five currencies.
The Jarque-Bera statistic is significant at the 1% level for all series, suggesting that foreign exchange returns are highly non-normal. The excess kurtosis and skewness indicate that the empirical distributions of the foreign exchange returns have fat tails and are skewed. We also compute the LM test of Engle (1982) to test heteroskedasticity.[17] This statistic is significant, indicating that all currencies

[15] Yilmaz (2003) and Chuluun et al. (2010) employ fixed-length moving windows with 1,000 daily and 260 weekly observations, respectively.

[16] The data are obtained from http://www.federalreserve.gov/Releases/h10/hist.

[17] The LM test is applied on the residuals of the ARMA model, where the lag length is selected based on the Akaike and Schwarz information criterion.

show strong conditional heteroskedasticity. Accordingly, statistical inference for randomness using the martingale tests should be based on the heteroskedasticity-adjusted statistic.

For the weekly data (Panel B), all the returns show evidence of significant excess skewness and excess kurtosis and are not normally distributed.

3.3 Evaluating time-varying return predictability

For daily data, we use moving sub-sample window of 2 years (about 500 observations). The sample size of around 520 is large enough to avoid possible small sample deficiencies for the tests involved. The first subsample window starts on January 1st, 1974 and ends on December 31st, 1975. After the martingale tests for the first subsample is calculated, the window is moved five daily observations forward, and the martingale tests are recalculated.[18] For the weekly data, we choose a window length of 104 weeks (2 years).[19] The test statistics for all windows are obtained, they are plotted, and their behavior over time is analyzed. Moving fixed-length subsample windows enables one to identify shocks that significantly alter the exchange rate behavior. These shocks on the exchange rate behavior are identified by significant jumps in the test statistics.

Figures 1–6 report the results of the AVR, GSS and DL tests with the fixed-length moving windows which are plotted for their p-values for the daily data, whereas Figures 7–12 display the results for the weekly data. The red and blue lines indicate the 5% and 10% significance levels. Overall, the results show that all the nominal exchange rates deviate from the martingale in some periods, which can be common to some currencies, since some p-values are in the rejection region for both daily and weekly data. This indicates that the currencies do not follow a martingale difference sequence on the entire period 1975–2009 as well as during the Great Moderation period,[20] but we observe some non-martingale episodes implying predictability of exchange rates for which it was possible generate abnormal returns through speculation. This finding is consistent with the implications of the AMH but not with the EMH.

For the daily data (Figures 1–6), the three tests reject the martingale hypothesis for

[18] It was decided to increase the sample size by five daily observations at a time to save on computer time.

[19] We have also considered others window lengths, and we found that the results are not sensitive to the different choices of window length.

[20] See, e.g., Kim et al. (2008), Gali and Gambetti (2009) and Enders and Ma (2011) on the sources of the Great Moderation.

CA$ and JPY, the AVR and DL test statistics also for AU$ and GBP, and the AVR test for CHF with Volcker disinflationary policy period in 1980 to stabilize the inflation with several coordinated interventions of the major central banks. As the subsample window is moved to include the data for 1982, the three tests for AU$, the AVR test for CA$, JPY and GBP, and the DL test for CHF are close to the 10% critical level with the intervention of the Reagan administration for concerted interventions with major central banks after June 1982 to slow down the appreciation of the dollar. Note also the abandon of the crawling peg system for AU$ in favor of an indepently floating exchange rate in 1983 which can affect the martingale behavior. The AVR and GSS test statistics for CA$, JPY and CHF, the AVR and DL tests for AU$ and the DL test for GBP started to move to the rejection region from the end of 1985 indicating a strong deviation from martingale behavior with the coordinated intervention period that started after the Plaza Accord in September 1985. This agreement marks a drastic change in the policy stance of the major central banks in terms of the movements of exchange rates since G7 finance ministers agreed to intervene in the worldwide foreign exchange markets in a concerted fashion when they find it necessary. Most of the concerted interventions have taken the form of selling US$ against other major currencies (Dominguez, 1990). As the subsample windows are moved forward to include the data for 1987 in the subsample windows, test statistics reject the martingale hypothesis for CA$, JPY and GBP for the AVR and DL tests and AU$ for the GSS and DL tests with the interventions of the Louvre Accord period after February 1987. This agreement reenforces the concerted interventions of the leading central banks (US Federal Reserve, Bundesbank and Bank of Japan) by setting unannounced and secret target bands for their exchange rates, beyond which central banks have agreed to intervene. AU$ and GBP have a non-martingale behavior when the subsample window moves to include the data for 1995 with the coordinated interventions of the G7 central banks to help the dollar. The AVR test statistics for AU$, CA$ and GBP started to move to the rejection region during the 2008-2009 financial crisis period, but it is not the case from the GSS test statistics. This crisis is characterized by the massive central banks and governmental interventions. Note that, contrarily to Yilmaz (2003), we do not find rejection of the martingale hypothesis for the Gulf war period. This finding can be explained by the fact that we employ tests with superior small sample properties to those used by Yilmaz (2003), namely the Chow-Denning and Richardson-Smith joint tests (Kim, 2006).

Furthermore, some non-martingale periods are more specific to each currency: The outbreak of the Exchange Rate Mechanism (ERM) crisis in 1992 for GBP, after

excessive speculative attacks where the Bank of England intervenes heavily to defend its ERM exchange rate; the Japanese recession in 1993 for JPY, with concerned interventions of the US Federal Reserve and the Bank of Japan intervene to support the JPY; the low interest rate policy of the Bank of Canada[21] in 1996, which leads to a rapid decline in the value of the CA$; the East-Asian financial crisis in 1997, which implies a drop of the AU$; the intervention of the Japan central bank in 1999 to support the JPY; the rise of commodity prices and Canadian domestic inflation in 2004 can explain the rise of the CA$; and the US dollar's massive budget and current account deficits as well as the gold selling program of the Swiss National Bank in 2005 imply the drop of the CHF.

Figures 7–12 display less non-martingale episodes from the weekly data than from the daily data for the AVR and DL tests, except for the GSS test. The DL test also exhibits long period of non-martingale behavior between 1980 and 1985 for all the currencies, except for the CA$. The difference between the daily and weekly data can be explained by the effect of temporal aggregation or by bid-ask spread and non-trading and asynchronous prices.

4 Conclusion

This study examined return predictability of major foreign exchange rates by testing for martingale difference hypothesis (MDH) using daily and weekly nominal exchange rates from 1975 to 2009. We used alternative MDH tests for linear and nonlinear dependence, which include wild bootstrap automatic variance ratio test, generalized spectral test, and consistent tests. We evaluated time-varying return predictability by applying these tests with fixed-length moving sub-sample windows of 2 years. While exchange rate returns have been found to be unpredictable most of times, we observed episodes of statistically significant return predictability. They have been associated with coordinated central bank interventions and the subprime mortgage crisis in 2007. This finding suggested that return predictability of foreign exchange rates occurs from time to time depending on changing market conditions, which is consistent with the implications of the adaptive markets hypothesis but not with the efficient market hypothesis, namely that dynamic market conditions govern the degree of exchange rate efficiency.

[21] Note that the Bank of Canada has no specific target value for the Canadian dollar and has not intervened in foreign exchange markets since 1998. The Bank's official position is that market conditions should determine the worth of the Canadian dollar.

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Table 1: Selected studies on the MDH for major exchange rate markets.

Studies	Sample	Methodologies	Comments
Hsieh (1988)	1974–1983 (D)	autocorrelation	not MDH for CA, FR, GE, JP, UK
Liu and He (1991)	1974–1989 (W)	variance ratio	not MDH for CA, FR, GE, JP, UK
Fong and Ouliaris (1995)	1974–1989 (W)	spectral	not MDH for CA, FR, GE, JP, MDH for UK
Fong et al. (1997)	1974–1989 (W)	variance ratio	not MDH for FR, GE, JP; MDH for CA, UK
Hong (1999)	1976–1995 (W)	spectral	not MDH for GE
Wright (2000)	1974–1996 (W)	variance ratio	not MDH for CA, FR, GE, JP, UK
Lobato et al. (2001)	1976–1996 (D)	autocorrelation	MDH for GE, JP, SW, UK
Yilmaz (2003)	1974–2001 (D)	variance ratio	not MDH for CA, FR, GE, JP, UK, IT, SW
Hong and Lee (2003)	1975–1998 (W)	spectral	not MDH for CA, FR, JP, GE, UK
Kuan and Lee (2004)	1974–1989 (W)	spectral	MDH for CA, FR, GE, JP, UK
Chang (2004)	1974–1998 (D)	variance ratio	not MDH for JP inconclusive for CA, FR, GE, UK
Belaire-Franch and Opong (2005)	1999–2002 (D)	variance ratio	MDH for AU, NZ, JP, UK, NO, SE, SW, US; not MDH for CA
Escanciano and Velasco (2006)	1974–1989 (W)	spectral	not MDH for FR, GE, JP, UK inconclusive for CA
Horowitz et al. (2006)	1993–1996 (D)	autocorrelation	not MDH UK
Escanciano and Lobato (2009a)	1987–2007 (D)	autocorrelation	MDH for CA, JP, not MDH for UK
Escanciano and Lobato (2009b)	2004–2007 (D, W)	autocorrelation spectral	not MDH for CA, EU, JP, UK MDH for CA, JP, UK; not MDH for EU
Chortareas et al. (2010)	1999–2009 (D)	autocorrelation	MDH for AU, CA, JP, NO, NZ, SE, SW, UK, US
Chuluun et al. (2011)	1974–2006 (W)	variance ratio	not MDH for AU, CA, EU, GE, JP, NZ, NO, SE, SW, UK

Notes: D: daily; W: weekly. AU: Australian dollar; CA: Canadian dollar; EU: Euro; FR: French franc; GE: German mark; IT: Italian lira; JP: Japanese yen; NO: Norwegian kroner; NZ: New Zealand dollar; SE: Swedish krona; SW: Swiss franc; UK: British pound. US: United States dollar.

Belaire-Franch and Opong (2005) and Chortareas et al. (2010) investigate Euro-based exchange rates whereas the others studies on exchange rates are against the US dollar.

Table 2: Descriptive statistics for daily and weekly log exchange rate returns

	Mean	SD	Skewness	Kurtosis	JB	LM(10)
Daily data						
Australia	-6.63	0.69	-4.04*	99.31*	3608918*	116.4*
Canada	-1.23	0.38	-0.25*	18.42*	92016*	1718.4*
Japan	-11.8	0.65	-0.47*	8.78*	13229*	500.5*
UK	-3.80	0.61	-0.20*	7.90*	9319*	740.1*
Switzerland	-11.9	0.73	-0.05	6.35*	4331*	473.5*
Weekly data						
Australia	-3.30	0.15	-2.89*	32.74*	70903*	26.4*
Canada	0.63	0.09	0.17*	11.45*	5528*	606.9*
Japan	-5.90	0.14	-0.52*	5.81*	692*	94.7*
UK	1.82	0.14	-0.43*	6.77*	1154*	175.2*
Switzerland	-6.10	0.16	-0.31*	4.64*	236*	65.4*

* means significant at the 5% level. The mean values are multiplied by 10^5 and 10^4 for daily and weekly data, respectively. The standard error values are multiplied by 10^2 and 10 for daily and weekly data, respectively.

Figure 1: Results of the AVR test for daily data

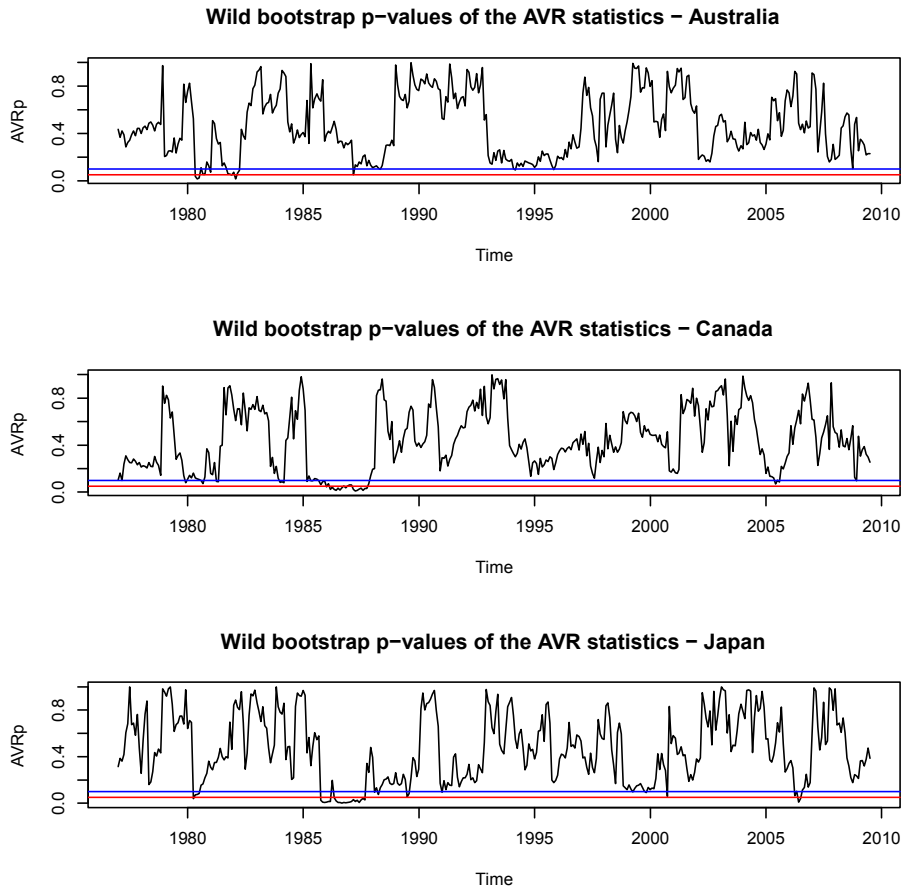

Figure 2: Results of the AVR test for daily data

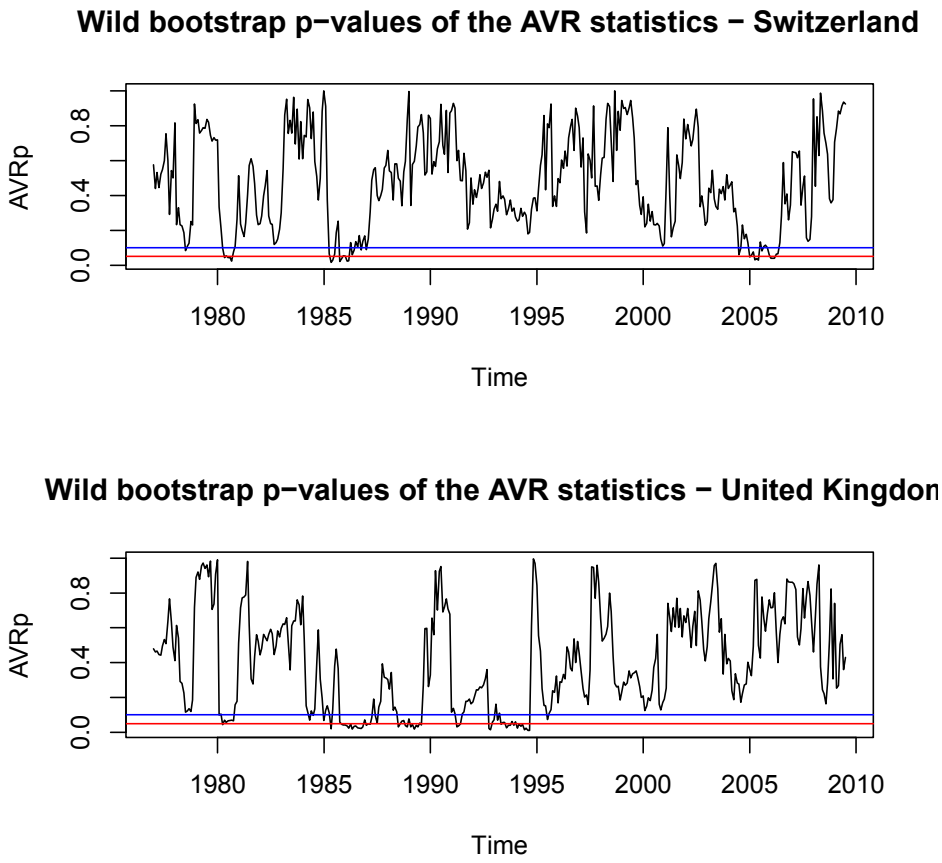

Figure 3: Results of the GSS test for daily data

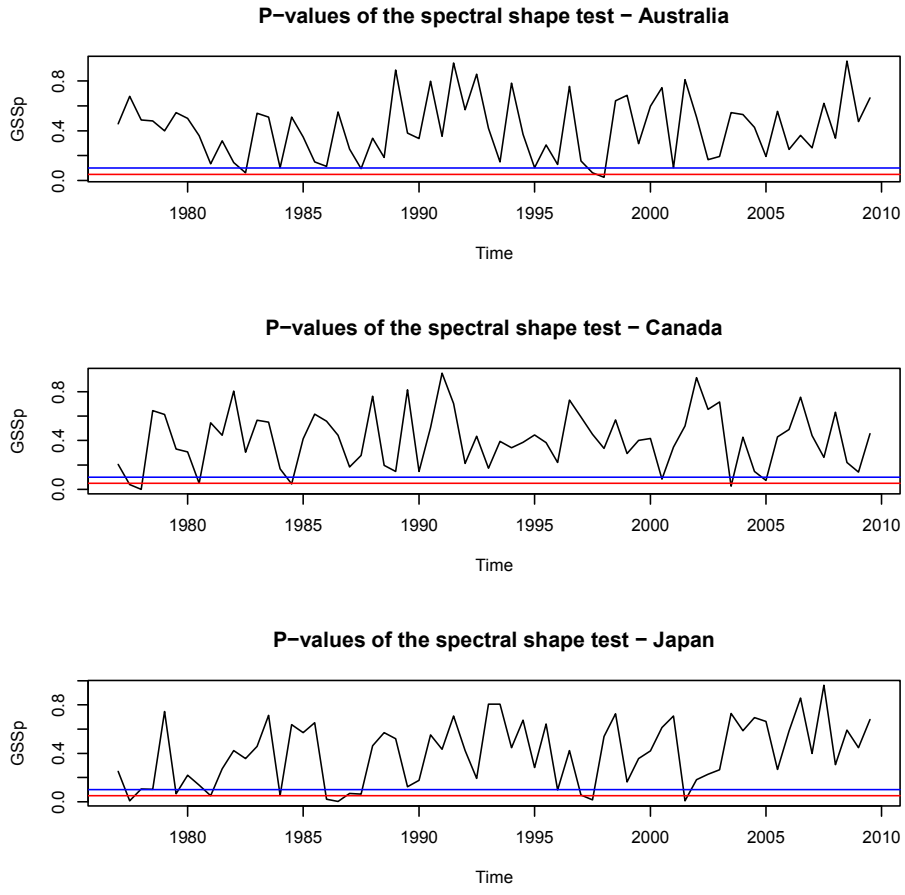

Figure 4: Results of the GSS test for daily data

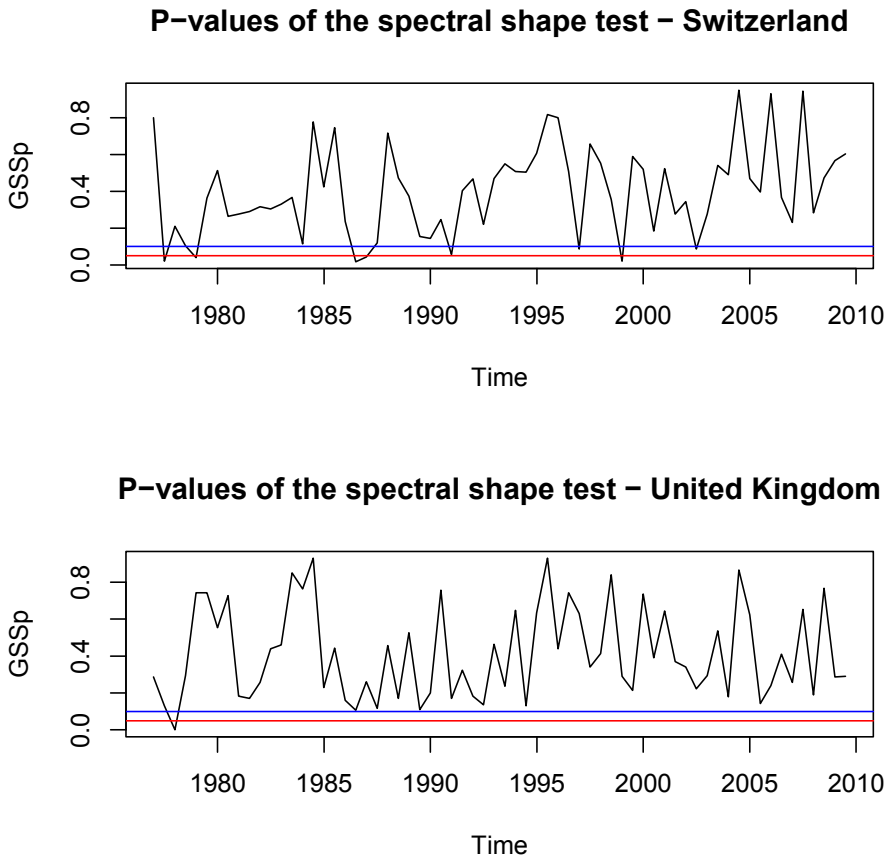

Figure 5: Results of the DL test for daily data

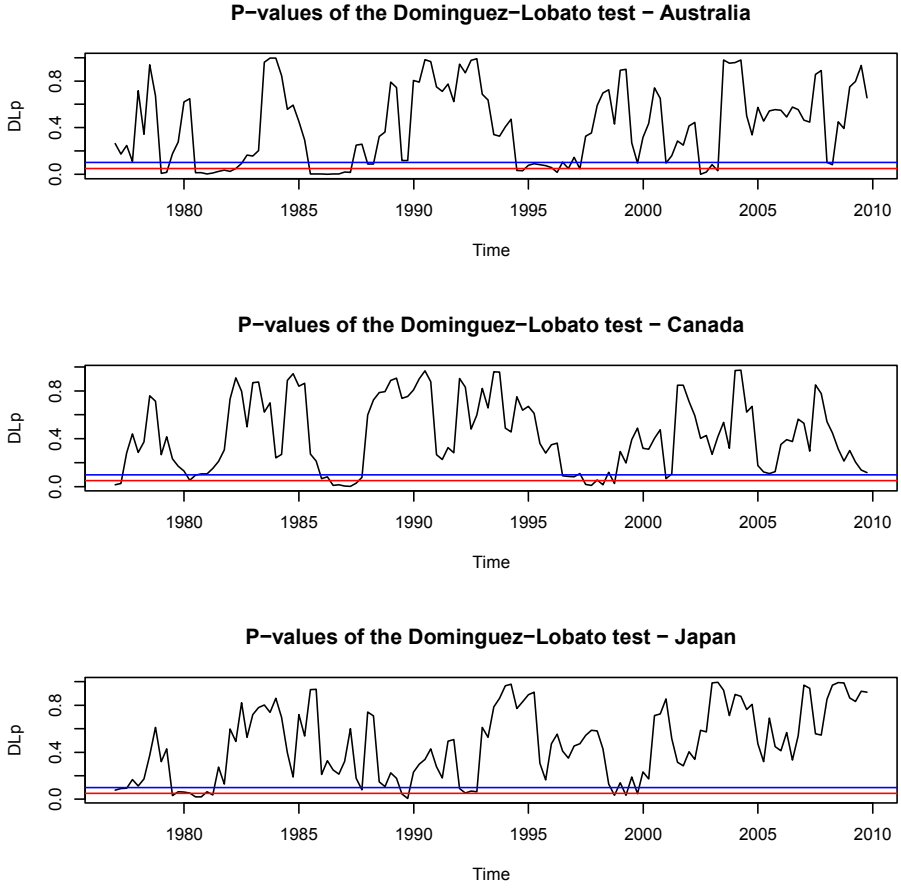

Figure 6: Results of the DL test for daily data

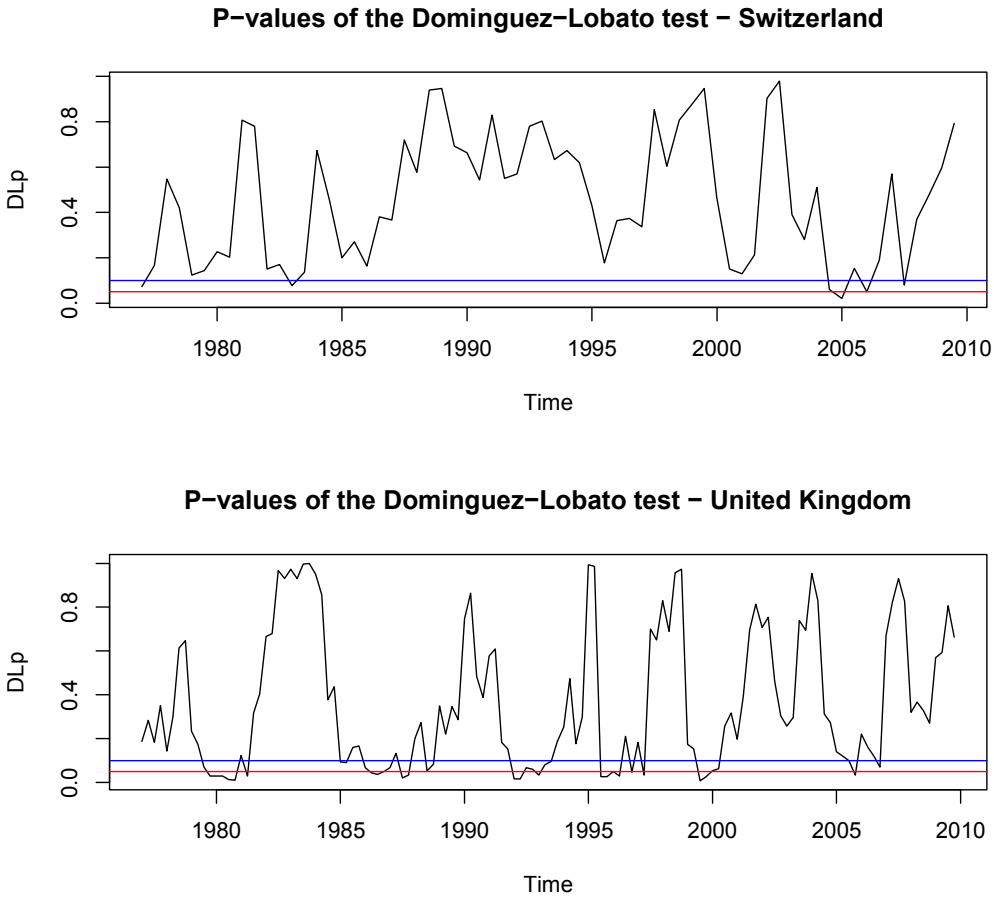

Figure 7: Results of the AVR test for weekly data

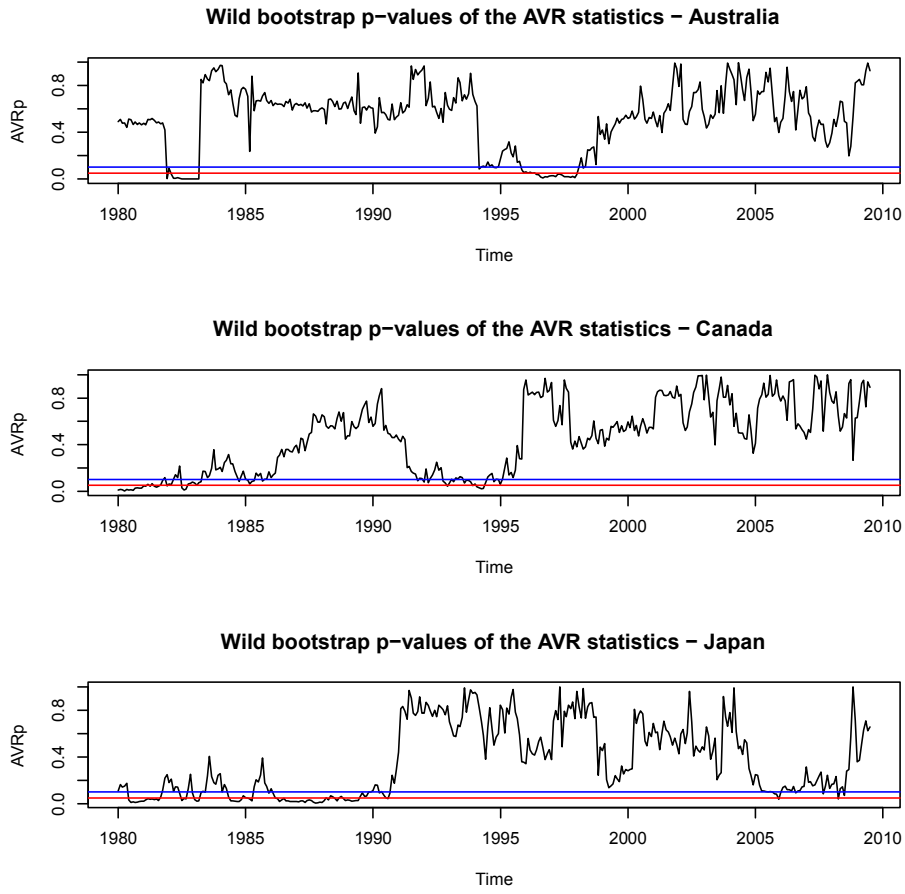

Figure 8: Results of the AVR test for weekly data

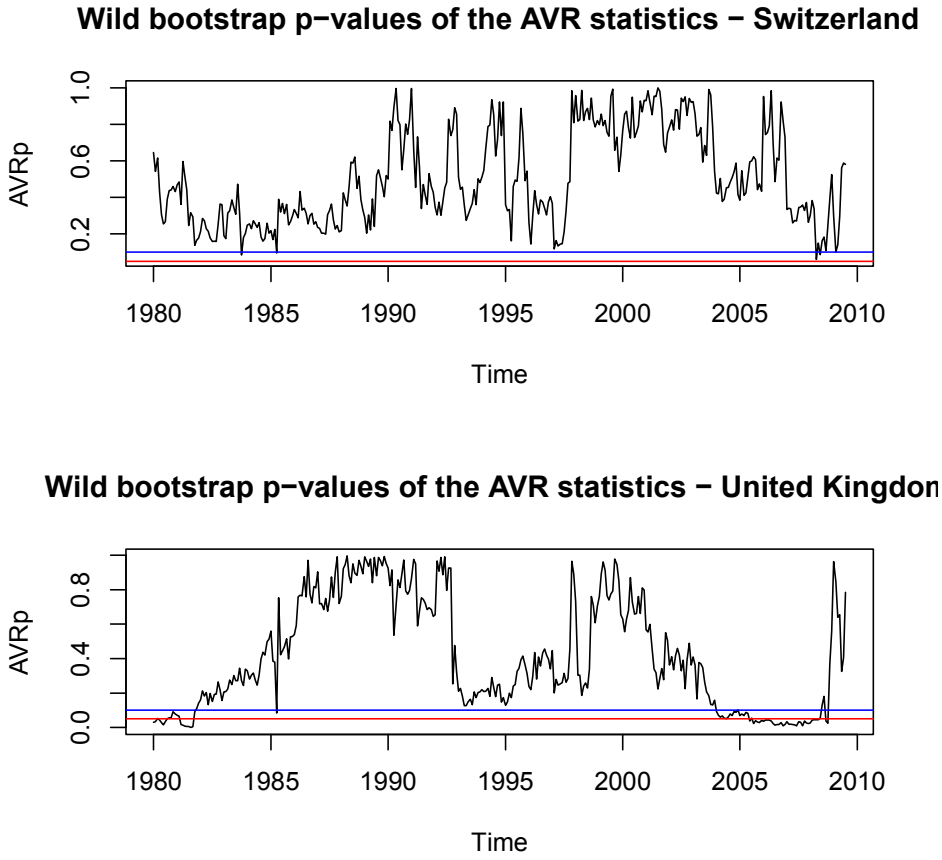

Figure 9: Results of the GSS test for weekly data

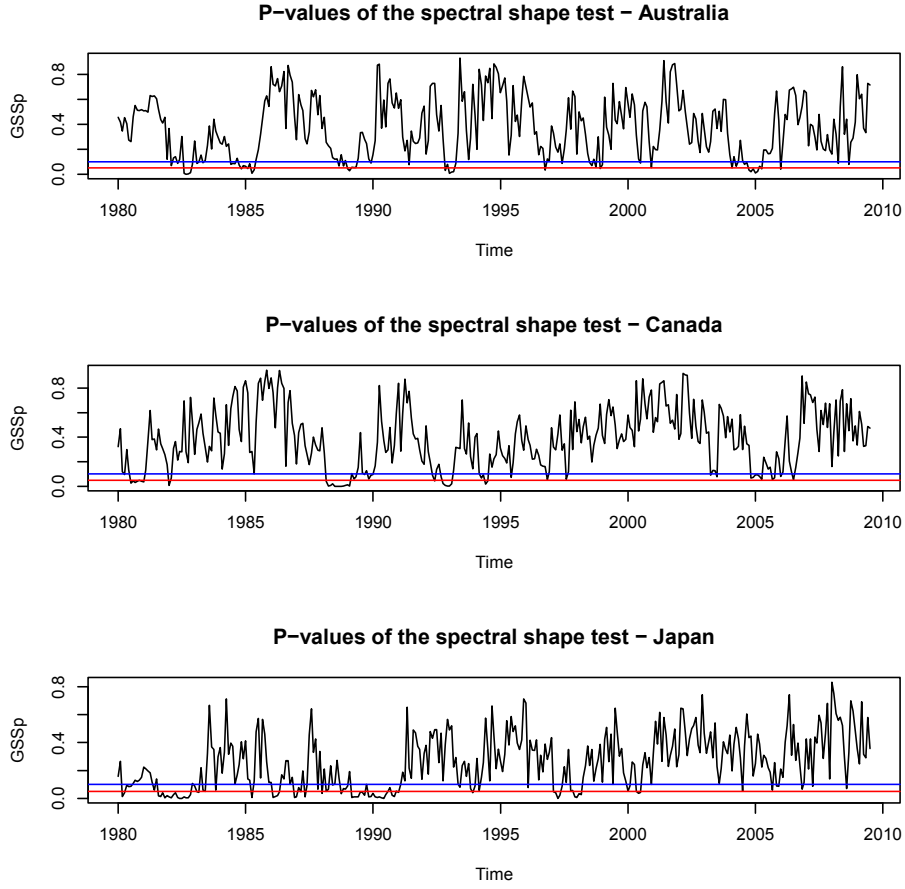

Figure 10: Results of the GSS test for weekly data

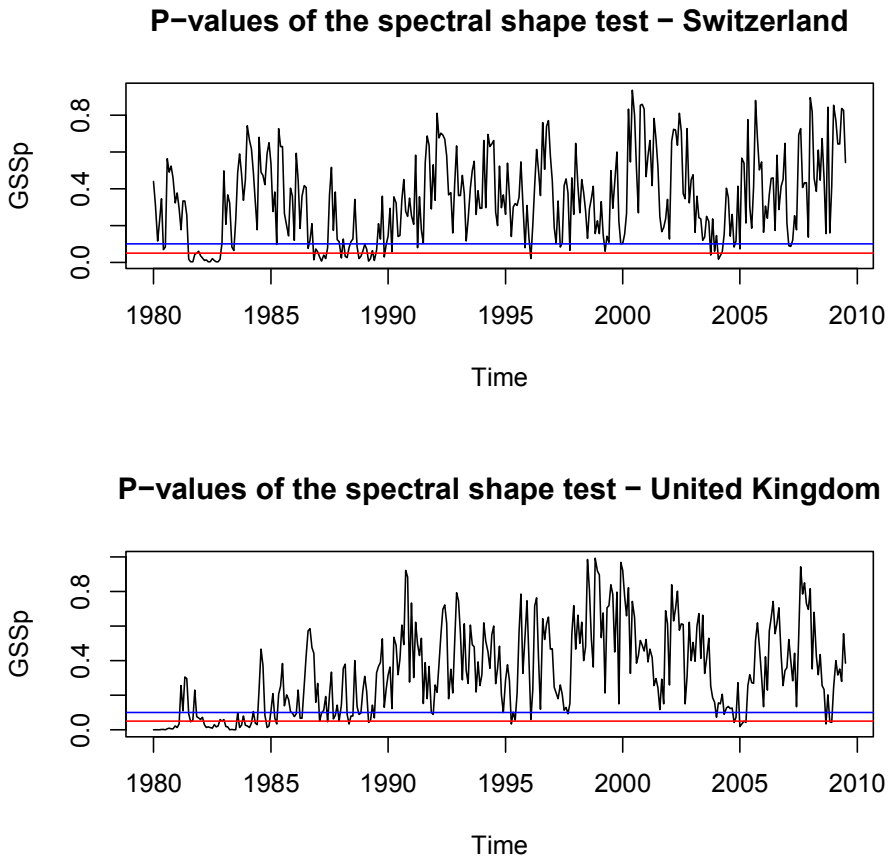

Figure 11: Results of the DL test for weekly data

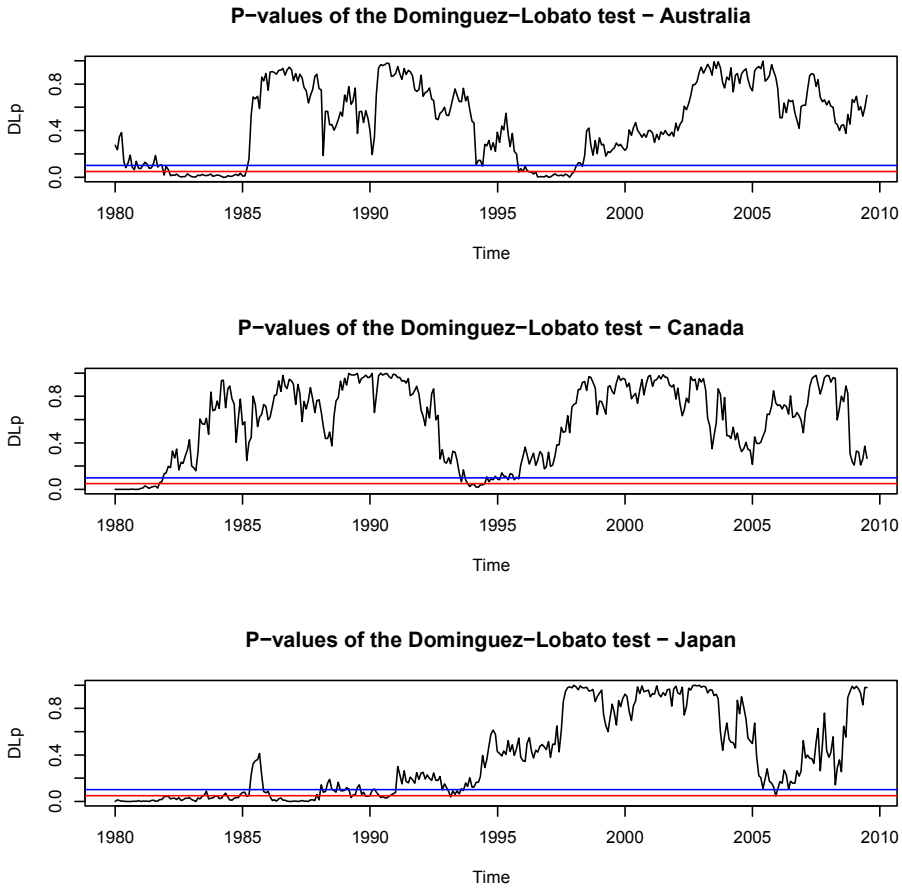

Figure 12: Results of the DL test for weekly data