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Exchange-rate return predictability and the adaptive markets hypothesis: Evidence from major foreign exchange rates

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A B S T R A C T

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 three alternative tests for the MDH, which include the wild bootstrap automatic variance ratio test, generalized spectral test, and Dominguez–Lobato consistent tests. We evaluate time-varying return predictability by applying these tests with fixed-length moving sub-sample windows. While exchange rate returns are found to be unpredictable most of times, we do observe a number of episodes of statistically significant return predictability. They are mostly associated with the major events such as coordinated central bank interventions and financial crises. This finding suggests that return predictability of foreign exchange rates occurs from time to time depending on changing market conditions, consistent with the implications of the adaptive markets hypothesis.

1. Introduction

One of the earliest and most enduring questions in economics and finance is whether prices of financial assets are predictable. The efficient market hypothesis (EMH) of Samuelson (1965) and Fama (1965) states that asset prices fully and instantaneously reflect all available and relevant information.

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Since price adjustment to a new piece of information is instantaneous and accurate, the returns cannot be predicted. As a result, prices in an efficient market follow a random walk or a martingale process.[1] Under the weak-form efficiency where the information set consists of past prices and returns, future prices and their returns are purely unpredictable based on past price information. Most of the studies for the EMH on financial markets have tested whether the returns follow a martingale difference sequence (MDS), where the returns are uncorrelated with the past values. If the foreign exchange market is weak-form efficient, the nominal exchange rate follows a martingale sequence and its returns are purely unpredictable based on past price and return information. For these reasons, the return predictability has been an important issue related to the market efficiency in the weak-form.

There are several alternatives explanations for predictability in foreign exchange 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 and regulatory arrangements, as they may affect the degree of foreign banks to access the foreign exchange markets and products; (v) the overshooting or undershooting phenomenon of exchange rates (Liu and He, 1991); and (vi) the central bank intervention (Dominguez and Frankel, 1993; Yilmaz, 2003; Beine et al., 2009).[2]

There have been numerous studies that tested the MDH in major foreign exchange rates. Since Meese and Rogoff (1983) showed that the structural models of exchange rate determination provide inferior out-of-sample forecasts to those implied by an MDS, many studies strived to uncover the empirical regularities in exchange rate behavior. In the literature, several alternative methods have been used to test for 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.[3] These methods have been used in many empirical applications on foreign exchange rates: see 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) and data frequencies (weekly or daily).

Recently, Lo (2004, 2005) proposed the adaptive markets hypothesis (AMH), which gives a framework to reconcile the EMH with the notion of bounded rationality.[4] An important implication of the AMH is that return predictability may arise time to time, due to changing market conditions (cycles, bubbles, crashes, crises …) and institutional factors. For the foreign exchange markets, a number of studies found that changing market conditions, caused by the events such as coordinated central bank intervention (LeBaron, 1999; Jeon and Lee, 2002; Yilmaz, 2003), Asian financial crisis (Jeon and Seo, 2003; Ahmad et al., 2011; Al-Khazali et al., 2011, 2012), and the global financial crisis (Ahmad et al., 2011), can affect

[1] See Escanciano and Lobato (2009b) for a distinction between random walk and martingale process.

[2] Note that no consensus has been reached on the effect of central bank's 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, 2006). 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. See Menkhoff (2010) for a discussion on foreign exchange interventions.

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

[4] 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., 2011). 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 participants, institutions and business conditions change.

market efficiency and other market features. 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 of 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.

Lim and Brooks (2010) reviewed the studies for time-varying weak-form market efficiency in stock returns and categorized them into three approaches: (i) non-overlapping sub-period analysis, (ii) time-varying parameter model, and (iii) rolling estimation window. In this study, we use the approach of moving sub-sample window to capture the dynamically changing return predictability under the AMH. To the best of our knowledge, Yilmaz (2003), Chiang et al. (2010), Belaire-Franch and Contreras (2011), and Chuluun et al. (2011) are the only studies that evaluate the MDH using time-varying measures in foreign exchange rates, but without an explicit link with the AMH.

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, which cover the periods of major coordinated central bank interventions and financial crises. We measure the degree of return predictability using three alternative tests for the MDH, namely the wild bootstrap automatic variance-ratio test of Kim (2009), the generalized spectral shape test of Escanciano and Velasco (2006), and the consistent tests of Dominguez and Lobato (2003). These tests are capable of detecting linear and non-linear dependence, being robust to non-normality and conditional heteroscedasticity that are typical features of foreign exchange rates (see, for details, Charles et al., 2011).

The remainder of this paper is organized as follows: Section 2 presents the alternative tests for the MDH adopted in this paper with a survey of the tests used in previous studies; Section 3 provides the details of the data and reports the empirical results, along with a brief survey of past empirical studies. Section 4 provides further discussions and the conclusion is drawn in Section 5.

2. Tests for martingale difference hypothesis

2.1. A brief survey of the tests

In testing for market efficiency or return predictability, the variance ratio (VR) test has been widely used. Since Lo and MacKinlay (1988) propose its 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).[5] 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; Fong et al., 1997). However, these choices are entirely arbitrary and adopted without any concrete statistical justifications. In view of this, Choi (1999) proposes an automatic variance ratio (AVR) 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 heteroscedasticity and has found that the test shows size distortion. Kim (2009) proposes wild bootstrapping of the test, which 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 for

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

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 and that they are valid under a restrictive condition that the returns are identically and independently distributed. Recently, a series of papers propose modified portmanteau tests 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 and Lobato (2009a) report that their automatic test shows desirable small sample properties such as correct size and high power, under conditional heteroscedasticity. They also find that it is more powerful than the robustified tests of Lobato et al. (2001, 2002), where the choice of lag orders is arbitrarily made.

Andrews and Ploberger (1996) propose another approach to testing for serial correlation, which is designed for the time series generated by an ARMA(1,1) model under the alternative hypothesis. 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 the generalization of the Box–Pierce test. They find that their generalized Andrews–Ploberger tests have satisfactory power properties compared to the generalized Box–Pierce test and the Deo (2000) tests.

The above-mentioned tests are (linear) autocorrelation-based tests, which are designed to capture the linear dependence of return on its own past. However, given the evidence of non-linear dependence in asset returns, evaluation of linear dependence only may be restrictive. The generalized spectral shape test of Escanciano and Velasco (2006) is capable 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 Escanciano and Velasco (2006), the test is more powerful than its competitors such as Deo (2000), Dominguez and Lobato (2003), Kuan and Lee (2004) and Hong and Lee (2003, 2005).

Recently, Charles et al. (2011) conduct an extensive Monte Carlo experiment to find that the wild bootstrap AVR test of Kim (2009), the generalized spectral shape (GSS) test of Escanciano and Velasco (2006) and the consistent test of Dominguez and Lobato (2003) (called DL hereafter) 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 non-linear dependence. These tests are also robust to non-normality and unknown forms of conditional and unconditional heteroscedasticity. In the next subsections, we present the details of these three tests, which are adopted in this paper.

2.2. Automatic variance ratio test

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

$$\hat{V}R(k) = 1 + 2\sum_{i=1}^{T-1} k\left(\frac{i}{k}\right)\hat{\rho}(i) \tag{1}$$

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

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

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,

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

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), Charles and Darné (2009b), Belaire-Franch and Opong (2010), and Chortareas et al. (2011) investigate euro-based exchange rates whereas the others studies on exchange rates are against the US dollar. Al-Khazali et al. (2011, 2012) analyze exchange rates relative to three benchmark currencies (US dollar, euro, and Japanese yen).

$$AVR(k) = \sqrt{T/k}[\hat{V}R(k) - 1]/\sqrt{2} \underset{d}{\rightarrow} N(0,1) \tag{2}$$

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

Table 2
Selected studies on the MDH for major exchange rate markets.

Studies	Sample	Methodologies	Comments
Charles and Darné (2009b)	1999–2008 (D, W)	Variance ratio	MDH for AU, CA, NZ, JP, UK, SW, US; not MDH for NO, SE
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	Not MDH for CA, EU, JP, UK
		spectral	MDH for CA, JP, UK; not MDH for EU
Chiang et al. (2010)	1998–2006 (D)	Variance ratio	MDH for JP
Belaire-Franch and Opong (2010)	1999–2003 (D)	Variance ratio	MDH for AU, JP, NO, UK, US; not MDH for CA, NZ, SE, SW
Chortareas et al. (2011)	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
Belaire-Franch and Contreras (2011)	1987–2001 (D)	Variance ratio spectral	Not MDH for CA, FR, GE, JP, UK, IT, SW
Al-Khazali et al. (2011)	1993–2005 (D)	Spectral variance ratio	Not MDH for AU
Al-Khazali et al. (2012)	1993–2008 (D)	Spectral variance ratio	Not MDH for AU

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), Charles and Darné (2009b), Belaire-Franch and Opong (2010), and Chortareas et al. (2011) investigate euro-based exchange rates whereas the others studies on exchange rates are against the US dollar. Al-Khazali et al. (2011, 2012) analyze exchange rates relative to three benchmark currencies (US dollar, euro, and Japanese yen).

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 $AVR(k^*)$.

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

1) Form a bootstrap sample of size T as $Y_t^* = \eta_t Y_t$ $(t = 1, \ldots, T)$ 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 absolute value of the observed statistic $AVR(k^*)$.

2.3. Tests based on non-linear measures of dependence

Suppose Y_t follows a martingale difference sequence, and the null hypothesis of interest is $H_0 : E(Y_t|Y_{t-1}, Y_{t-2}, \ldots) = \mu$, where μ is a real number. Escanciano 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. Escanciano and Velasco (2006) note that the above null hypothesis is equivalent to the following condition:

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

where $\gamma_j(x)$ represents an autocovariance measure in a non-linear framework and x represents any real number. Escanciano 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

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

where $\hat{\gamma}_j(x) = (T-j)^{-1}\sum_{t=1+j}^{T}(Y_t - \overline{Y}_{T-j})e^{ixY_{t-j}}$ 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 $\hat{H}_0(\lambda, x) = \hat{\gamma}_0(x)\lambda$, and the statistic of interest to test for H_0 is constructed as

Table 3
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[a]	99.31[a]	36,018[a]	116.4[a]
Canada	−1.23	0.38	−0.25[a]	18.42[a]	92,016[a]	1718.4[a]
Japan	−11.8	0.65	−0.47[a]	8.78[a]	13,229[a]	500.5[a]
UK	−3.80	0.61	−0.20[a]	7.90[a]	9319[a]	740.1[a]
Switzerland	−11.9	0.73	−0.05	6.35[a]	4331[a]	473.5[a]
Weekly data						
Australia	−3.30	0.15	−2.89[a]	32.74[a]	70,903[a]	26.4[a]
Canada	0.63	0.09	0.17[a]	11.45[a]	5528[a]	606.9[a]
Japan	−5.90	0.14	−0.52[a]	5.81[a]	692[a]	94.7[a]
UK	1.82	0.14	0.43[a]	6.77[a]	1154[a]	175.2[a]
Switzerland	−6.10	0.16	−0.31[a]	4.64[a]	236[a]	65.4[a]

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.

[a] Means significant at the 5% level.

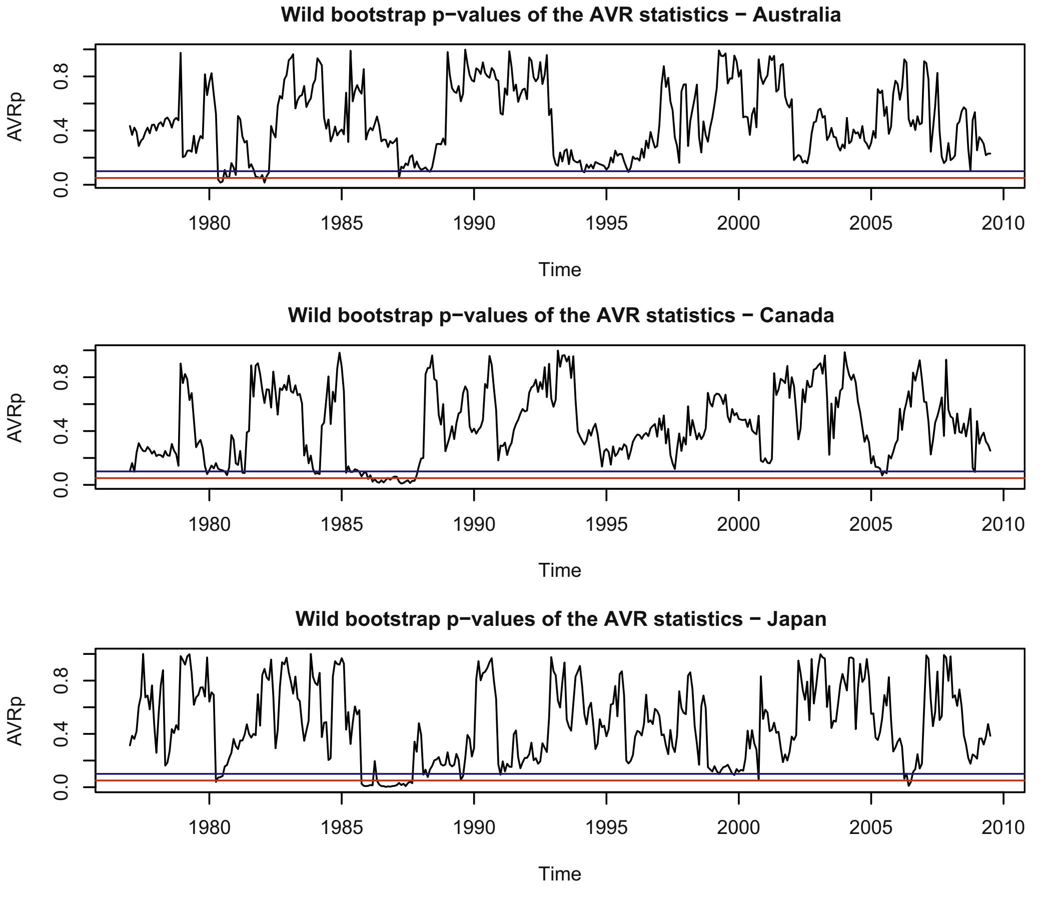

Fig. 1. Results of the AVR test for daily data.

$$S_T(\lambda,x) = (0.5T)^{\frac{1}{2}}\left\{\hat{H}(\lambda,x) - \hat{H}_0(\lambda,x)\right\}$$
$$= \sum_{j=1}^{T-1}(T-j)^{0.5}\hat{\gamma}_j(x)\frac{\sqrt{2}\sin(j\pi x)}{j\pi}$$

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

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

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

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

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

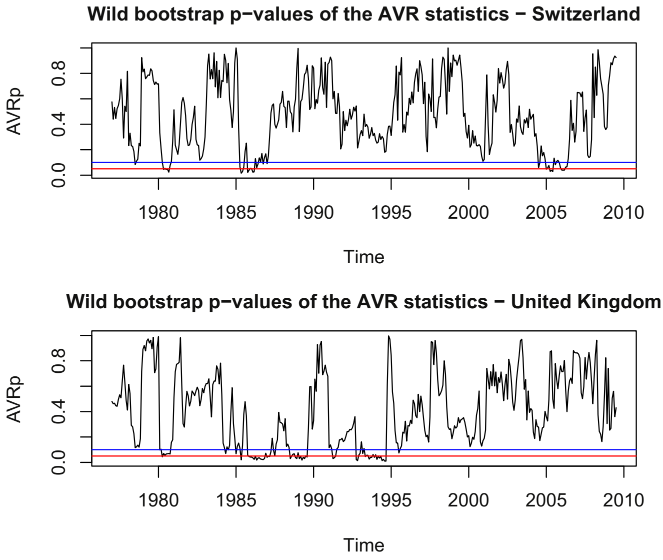

Fig. 2. Results of the AVR test for daily data.

$$CvM_{T,p} = \frac{1}{\hat{\sigma}^2 T^2} \sum_{j=1}^{T} \left[\sum_{t=1}^{T} (Y_t - \overline{Y}) 1\left(\tilde{Y}_{t,p} \le \tilde{Y}_{j,p} \right) \right]^2 ;$$
$$KS_{T,p} = \max_{1 \le i \le T} \left| \frac{1}{\hat{\sigma}\sqrt{T}} \sum_{t=1}^{T} (Y_t - \overline{Y}) 1\left(\tilde{Y}_{t,p} \le \tilde{Y}_{j,p} \right) \right|, \tag{4}$$

where $\tilde{Y}_{t,p} = (Y_{t-1,}, \ldots, Y_{t-p})$, 1() is the indicator function, and p is a positive integer.

The GSS and DL test statistics given in Eqs. (3) and (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 the MDH in major foreign exchange rates with overall mixed and sometimes inconclusive results. Tables 1and 2 present a brief summary of the selected studies, indicating the methodologies used, the types and frequencies of data employed, and the foreign exchange rates analyzed.

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 the Lo and MacKinlay (1988) VR tests 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 returns in nominal exchange rate series over the period 1974–1989. Fong et al. (1997), Wright (2000), Yilmaz

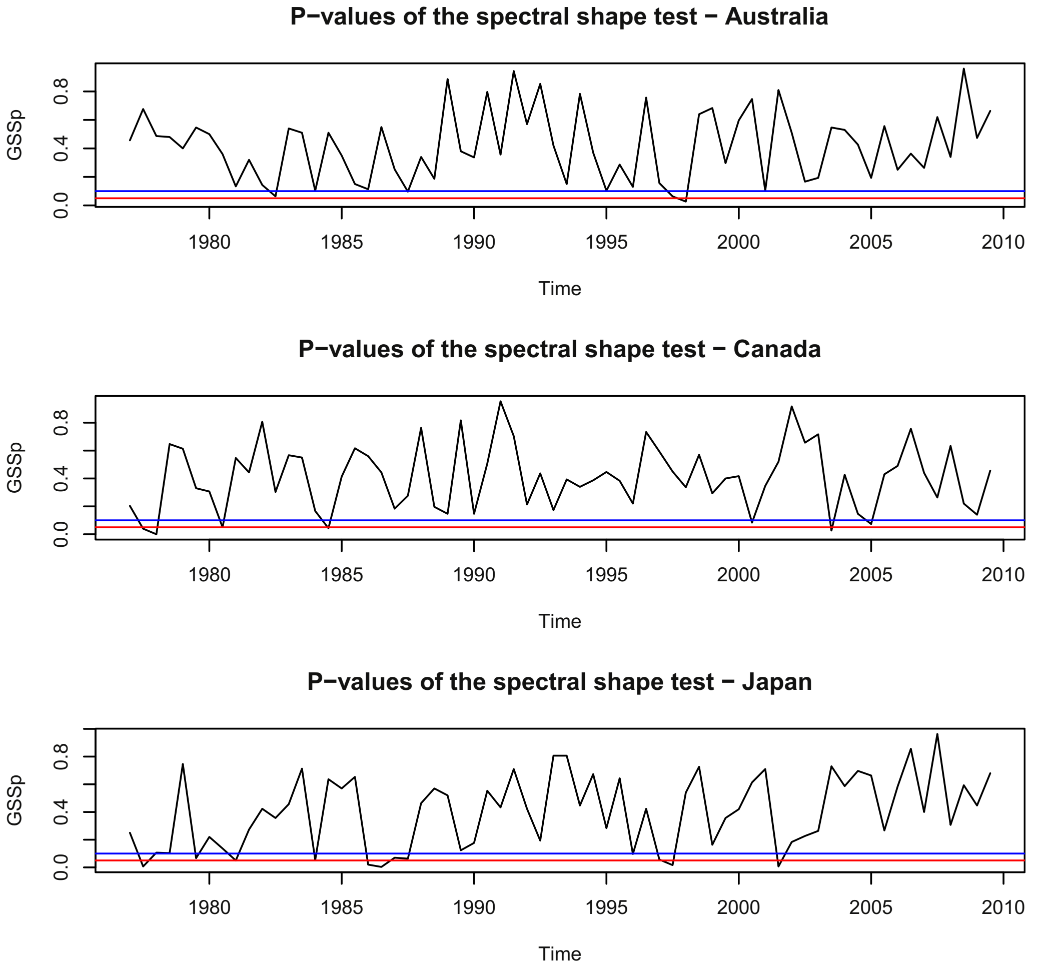

Fig. 3. Results of the GSS test for daily data.

(2003) and Chang (2004) re-examine the same five exchange rates using various VR tests. Wright (2000) and Yilmaz (2003) apply non-parametric sign and rank-based VR tests, Chow–Denning VR test (1993), and Richardson and Smith (1991) VR tests, confirming the results obtained by Liu and He (1991). Fong et al. (1997) find that the Richardson–Smith test fails to reject the MDH for all five currencies, whereas the Chow–Denning test continues to reject the hypothesis for the French franc, German mark, and Japanese yen. Chang (2004) provides evidence of rejecting the MDH for the Japanese yen, while the results for the other four currencies are inconclusive when daily data is employed using the Lo-MacKinlay VR test with a bootstrap resampling technique. Belaire-Franch and Opong (2005) use Wright's (2000) rank and sign VR tests, with size adjustment for multiple testing, 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) over the 1999–2002 period. Their results indicate that the Euro exchange rates are unpredictable and their markets are weak-form efficient. Charles and Darné (2009b) and Belaire-Franch and Opong (2010) re-examine the same Euro-based exchange rates of Belaire-Franch and Opong (2005) over the 1999–2008 period and the 1999–2003 period, respectively. Charles and Darné (2009b) apply the VR tests of Belaire-Franch and Contreras (2004) and Chen and

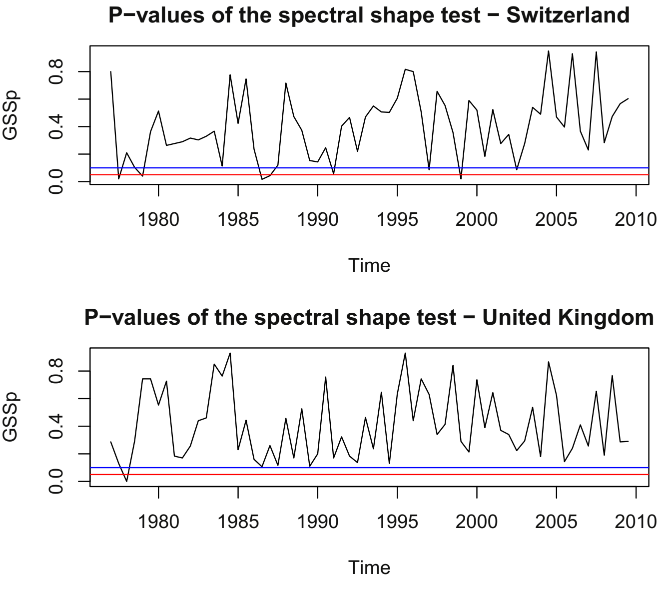

Fig. 4. Results of the GSS test for daily data.

Deo (2006), whereas Belaire-Franch and Opong (2010) use VR tests based on the subsampling approach proposed by Whang and Kim (2003). They find that the Euro exchange rates follow random walk.

Fong and Ouliaris (1995), Hong (1999), Hong and Lee (2003), Kuan and Lee (2004), and Escanciano and Velasco (2006) study foreign exchange rates using spectral tests that are capable of capturing non-linear dependence. 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 spectrum-based tests proposed by Durlauf (1991) and reject the MDH only for the British pound. Kuan 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 MDH for all exchange rates using the generalized spectral tests. This result is confirmed by Hong (1999) for the German mark on the period 1976–1995, using the generalized spectral test.

Hsieh (1988), Lobato et al. (2001), Horowitz et al. (2006), Escanciano and Lobato (2009a, 2009b), and Chortareas et al. (2011) analyze the MDH for various major exchange rates using (Box–Pierce type) autocorrelation tests. Hsieh (1988) investigates the five major currencies, daily from 1974 to 1983, using heteroscedasticity-adjusted Box–Pierce test and reject the null of the MDH. Lobato et al. (2001) use a modified Box–Pierce test using daily returns for the German mark, the Japanese yen, the Swiss franc, and the British pound to 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 for the period 1987–2007 using their automatic portmanteau test, whereas they reject the MDH for the British pound. Escanciano and Lobato (2009b) find that the Canadian dollar, Japanese yen and British pound have no linear dependence for the period 2004–2007, using a number of autocorrelation tests. This result is confirmed by Horowitz et al. (2006) for the British pound on the period 1993–1996 from a bootstrapped Box–Pierce test. Chortareas et al. (2011) 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), Chiang et al. (2010), Belaire-Franch and Contreras (2011) and Chuluun et al. (2011) are the only studies that evaluate the MDH from time-varying measures using moving sub-

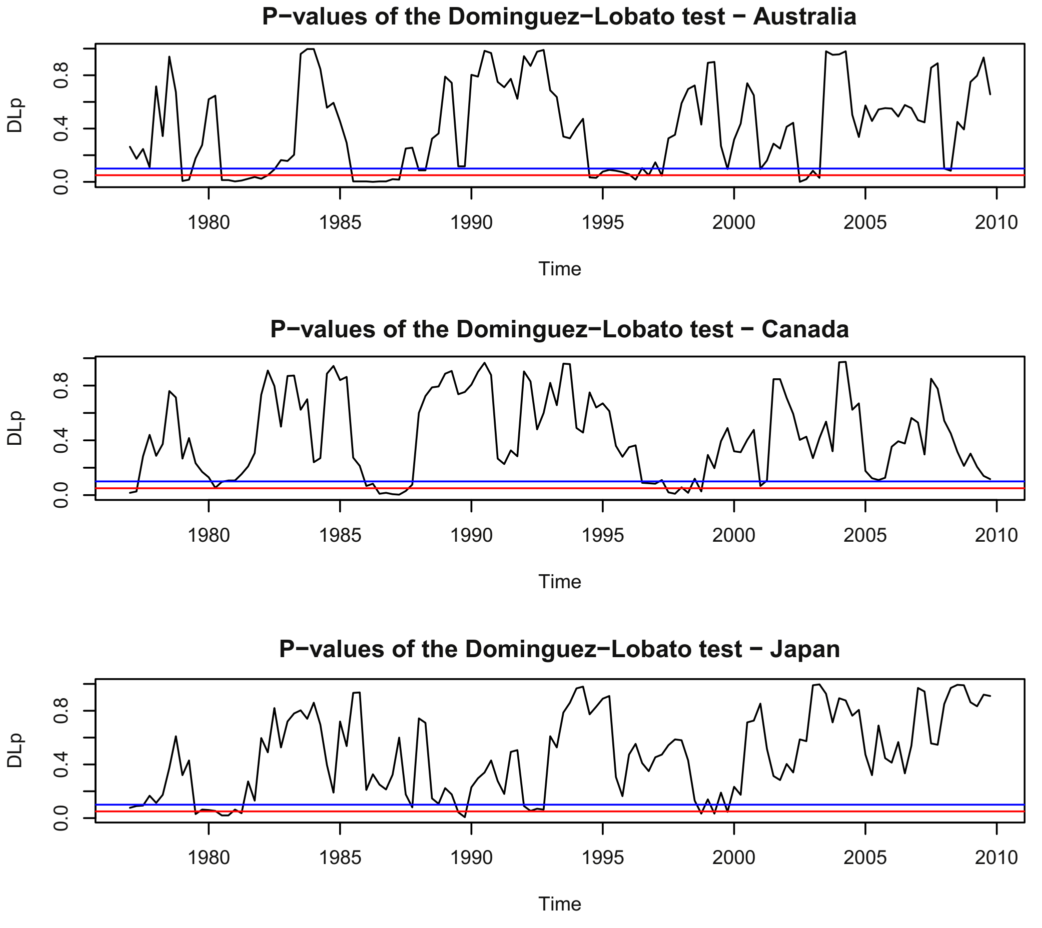

Fig. 5. Results of the DL test for daily data.

sample windows.[6] More precisely, Yilmaz (2003) use the VR tests of Chow and Denning (1993) and Richardson and Smith (1991); Chiang et al. (2010) use those of Lo and MacKinlay (1988), Wright (2000) and Chow and Denning (1993); while Chuluun et al. (2011) use those of Chow and Denning (1993), Lo and MacKinlay (1988), Wright (2000), along with the spectral test of Kuan and Lee (2004).

3.2. *Data and descriptive statistics*

We use daily nominal exchange rates, for the Australian dollar (AU$), British pound (GBP), Canadian dollar (CA$), Japanese yen (JPY), and Swiss franc (CHF) relative to the US dollar, which are major 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, with a total of 9274 observations. We also use weekly data 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

[6] Yilmaz (2003), Chiang et al. (2010), Belaire-Franch and Contreras (2011), and Chuluun et al. (2011) employ fixed-length moving windows with 1000 daily, 250 daily, 1000 daily, and 260 weekly observations, respectively.

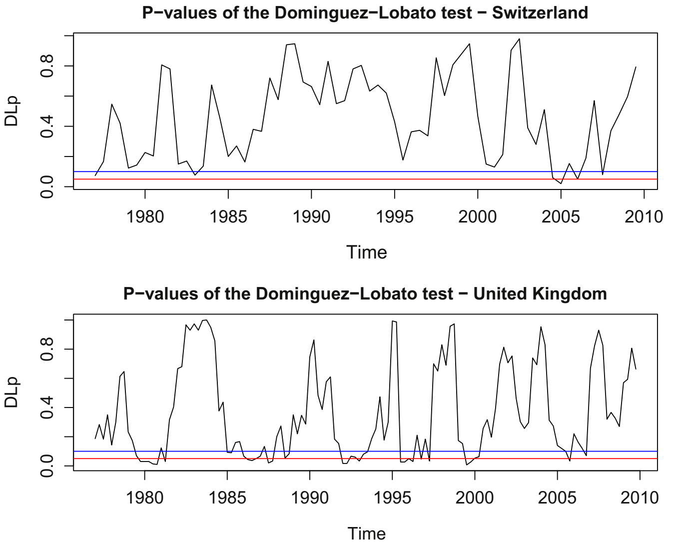

Fig. 6. Results of the DL test for daily data.

by the Federal Reserve Bank of New York for customs and cable transfers purposes), which are obtained from the Federal Reserve.[7]

We present descriptive statistics for the return series calculated as the first logarithmic difference of the nominal exchange rates for daily and weekly data in Table 3. For the daily data, in terms of standard deviation, CA$ exhibits the least volatility, while CHF displays the highest volatility. On average, US$ has depreciated against all five currencies during the data period. The Jarque–Bera test statistic is significant at the 1% level of significance for all series, indicating that the exchange returns are highly non-normal. The excess kurtosis and negative skewness values indicate that the empirical distributions of the returns exhibit substantially fatter tails (than the normal distribution) and asymmetric shape (with longer left tail). We also conduct the LM test of Engle (1982) for ARCH conditional heteroscedasticity.[8] This test statistic is significant for all rates, indicating that they show strong conditional heteroscedasticity. Similarly to the daily data, the weekly data show that all returns are non-normal with significant excess skewness and excess kurtosis, with strong evidence of conditional heteroscedasticity. As mentioned earlier, the MDH tests adopted in this paper are robust to these features.

3.3. Evaluating time-varying return predictability

For daily data, we use moving sub-sample window of 2 years, which consists of approximately 520 observations. This sample size is large enough to avoid possible small sample deficiencies for the tests involved. The first sub-sample window covers the period from January 2, 1974 to December 31st, 1975. After the tests are conducted for the first sub-sample, the window is moved five daily observations forward to lighten the computational burden, and the test statistics are recalculated. For the weekly data, we choose a window length of 104 weeks (2 years).[9] We plot the *p*-values of the test statistics over time. When they are less than 0.05 or 0.10, the return predictability is significant at 5% or 10% level of

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

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

[9] We have also considered others window lengths for both daily and weekly data, and we found that the results are not sensitive to the different choices of window length.

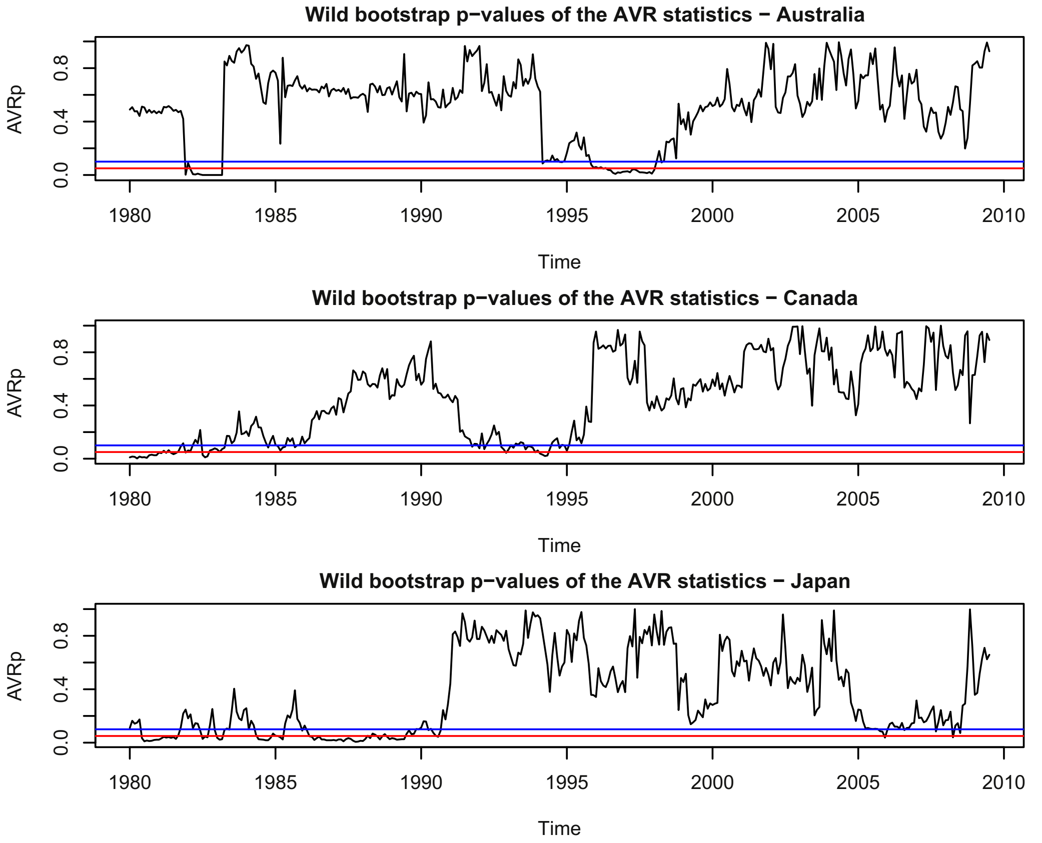

Fig. 7. Results of the AVR test for weekly data.

significance. In this way, the periods or episodes of statistically significant return predictability can be identified, which in turn can be related to the corresponding shocks and events.

Figs. 1–6 report the *p*-values of the AVR, GSS and DL tests for the daily data, while Figs. 7–12 for the weekly data. The two horizontal lines correspond to 0.05 and 0.10. Overall, the results show that all nominal exchange rates deviate from the martingale in a number of periods. This indicates that the currencies do not follow an MDS for the entire period 1975–2009, which includes the period of Great Moderation.[10] We clearly observe non-martingale episodes, which indicate periods of return predictability consistent with the implications of the AMH.

For the daily data (Figs. 1–6), the three tests reject the MDH for CA$ and JPY; the AVR and the DL tests also reject the MDH for AU$ and GBP; and the AVR test rejects the MDH for CHF in 1980. The timing corresponds to the Volcker disinflationary policy period where the inflation is stabilized with several coordinated interventions of the major central banks. As the sub-sample window moves to 1982, all three tests reject the MDH for AU$; the AVR test for CA$, JPY and GBP; and the DL tests for CHF, which coincide with the timing of the intervention of the Reagan administration for concerted interventions with major central banks to slow down the appreciation of the dollar. Note also the abandonment of the crawling peg system for AU$ in favor of an independently floating exchange rate in

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

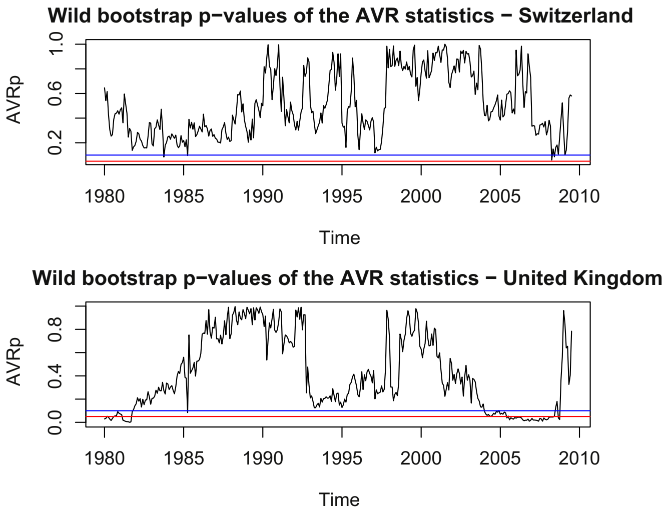

Fig. 8. Results of the AVR test for weekly data.

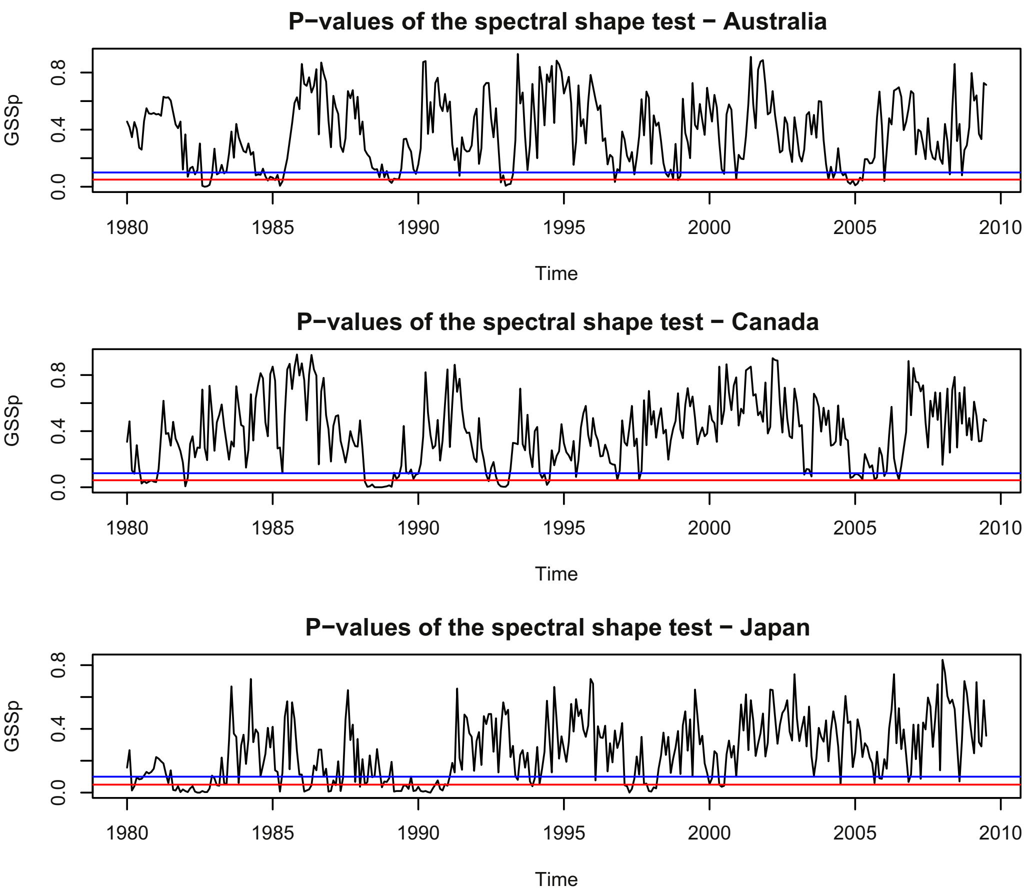

Fig. 9. Results of the GSS test for weekly data.

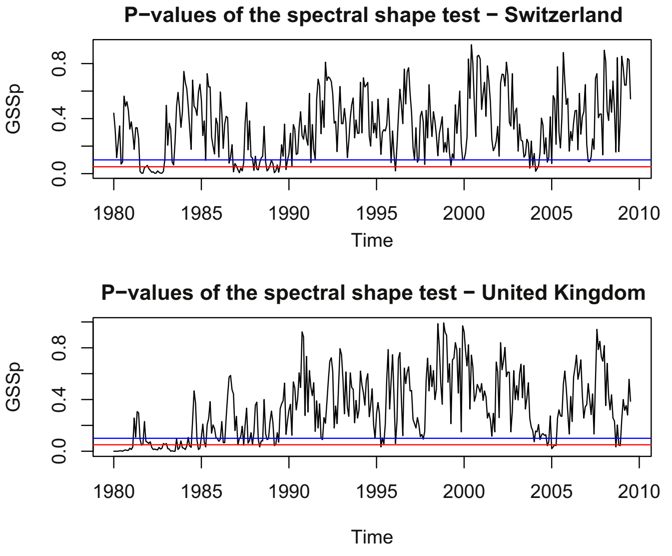

Fig. 10. Results of the GSS test for weekly data.

1983, which may have affected the martingale behavior. The AVR and GSS test for CA$, JPY and CHF; the AVR and DL tests for AU$; and the DL test for GBP start 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 sub-sample windows move forward to 1987, the AVR and DL tests reject the MDH for CA$, JPY and GBP; and the GSS and DL tests for AU$, with the interventions of the Louvre Accord period after February 1987. This agreement reinforces 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 show a non-martingale behavior when the sub-sample window moves to 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. This crisis is characterized by the massive central banks and government interventions. For example, the Bank of Canada (BoC), the Bank of England (BoE), the European Central Bank (ECB), the Federal Reserve (Fed), and the Swiss National Bank (SNB) reduced their policy interest rates in October 2008. The SNB and ECB cooperated to provide CHF liquidity in October 2008. During the 2008–2009 period, the BoE, the ECB, the Fed, the Bank of Japan (BoJ), and the SNB took joint measures to improve liquidity in short-term US dollar funding markets, in order to provide broad access to liquidity and funding to financial institutions.[11]

Note that, contrary to the findings of Yilmaz (2003), we do not find rejection of the MDH for the Gulf war period. We note that the Chow–Denning and Richardson–Smith joint tests that Yilmaz (2003) used

[11] Melvin and Taylor (2009) reviewed the events and implications of this crisis for exchange rate market, especially volatility, returns to currency investing, and transaction costs.

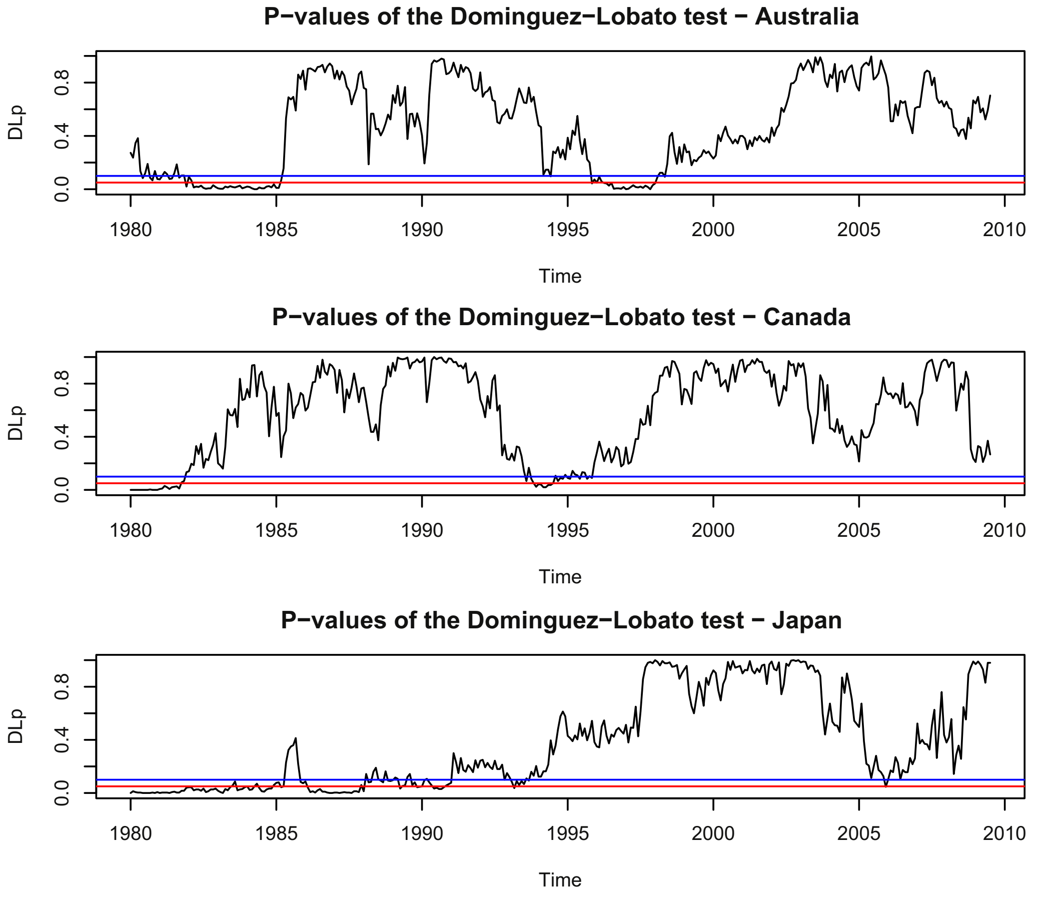

Fig. 11. Results of the DL test for weekly data.

suffer from size distortion in small samples, as documented in Kim (2006). In light of this, there is a possibility that the findings of Yilmaz (2003) may have provided incorrect inferential outcomes.

Furthermore, a number of non-martingale periods occur specifically to particular currencies. Namely, the outbreak of the Exchange Rate Mechanism (ERM) crisis in 1992 for GBP (AVR and DL tests), after excessive speculative attacks where the BoE intervenes heavily to defend its ERM exchange rate; the Japanese recession in 1993 for JPY (DL tests), with concerned interventions of the Fed and the BoJ to support the JPY; the low interest rate policy of the BoC[12] in 1996 (DL test), which leads to a rapid decline in the value of the CA$. Other cases include the East-Asian financial crisis in 1997, which caused a drop of the AU$ (GSS and DL tests); the intervention of the BoJ in 1999 to support the JPY (DL test); the rise of commodity prices and Canadian domestic inflation in 2004 (GSS test); and the US dollar's massive budget and current account deficits as well as the gold selling program of the SNB in 2005 caused the drop of the CHF (AVR and DL tests).

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

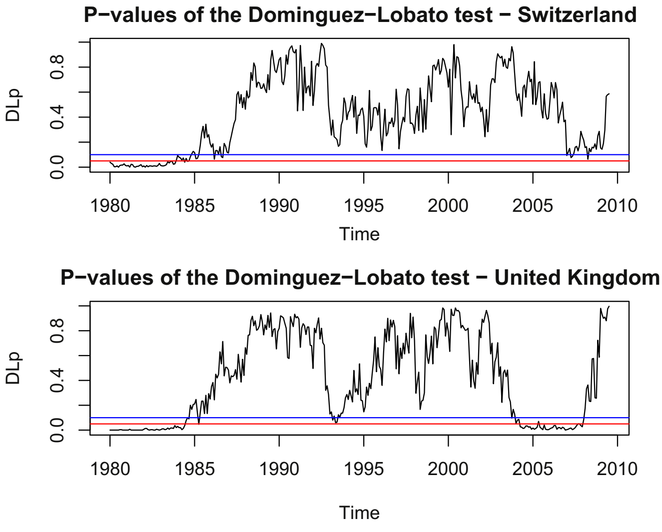

Fig. 12. Results of the DL test for weekly data.

4. Further discussions

In this paper, we use moving sub-sample windows to measure the degree of foreign exchange return predictability. There are two major benefits of this approach. First, it is capable of measuring time-varying return predictability, which is implied by the AMH where the degree of market efficiency (or return predictability) is changing over time depending on market conditions. Second, as Hsu and Kuan (2005; p. 608) point out, it is a useful tool to address the problem of data snooping bias, as an effective alternative to the statistical tests of White (2000) and Hansen (2005). It should be noted that

Table 4
Proportion of p-values less than 0.05 for the MDH tests.

	Daily data	Weekly data
AVR test		
Australia	0.013	0.101[a]
Canada	0.043	0.079[a]
Japan	0.066	0.192[a]
UK	0.043	0.000
Switzerland	0.113[a]	0.141[a]
GSS test		
Australia	0.015	0.065
Canada	0.061	0.076[a]
Japan	0.076	0.172[a]
UK	0.076	0.093[a]
Switzerland	0.015	0.144[a]
DL test		
Australia	0.182[a]	0.169[a]
Canada	0.083	0.079[a]
Japan	0.068	0.248[a]
UK	0.015	0.138[a]
Switzerland	0.159[a]	0.273[a]

For all entries, H_0: $q = 0.05$; H_1: $q > 0.05$ are tested, where q represents the population proportion of the p-values less than 0.05.

[a] Means the rejection of the H_0 against H_1 at 5% level of significance.

the moving sub-sample window approach is not intended for multiple testing in this paper, but as a means of measuring the degree of return predictability as stated above.

While we acknowledge that the approach we have taken is not a direct test for the AMH, there is no formal statistical test proposed to date as a direct test for the AMH, to the best our knowledge. We have observed that the periods of rejecting the MDH are closely related to the timing of major events, such as coordinated central bank interventions and financial crises (Asian and sub-prime mortgage). We argue that these major events alter the market conditions, which in turn change the degree of return predictability. Indeed, as mentioned earlier, there are accumulated evidence in the literature that these events change the conditions and ecology of foreign exchange markets (see, for example, Dominguez, 1998, 2003; LeBaron, 1999; Jeon and Lee, 2002; Jeon and Seo, 2003; and Ahmad et al., 2011). Hence, while our testing procedure is not a direct test for AMH, the outcomes of our tests are highly suggestive to the implications of the AMH. Note that Neely et al. (2009) adopt a similar approach in the context of the profitability of technical trading rules.

Although multiple testing is not intended in this paper as noted above, the p-values reported in the previous section provide an interesting result. Under the MDH, these p-values should be uniformly distributed, and the probability that a p-value is less than 0.05 should follow a binomial distribution.[13] Using a normal approximation to a binomial distribution, we can test $H_0 : q = 0.05$ against $H_1 : q > 0.05$, where q represents the population proportion of the p-values less than 0.05. Rejection of H_0 in favor of H_1 is evidence against the MDH. Table 4 reports the sample proportions of the p-values less than 0.05 for all currencies and tests. For daily data, at 5% level of significance, the null hypothesis is not rejected for most of cases; while, for weekly data, the null hypothesis is rejected for nearly all cases. This indicates that departure from the MDH is much stronger when the returns are evaluated at the weekly frequency.

5. Conclusion

This study examined return predictability of major foreign exchange rates by testing for martingale difference hypothesis (MDH) using daily and weekly data from 1975 to 2009. We used alternative MDH tests for linear and non-linear dependence, which include wild bootstrap automatic variance ratio test, generalized spectral test, and Dominguez–Lobato 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. We found that they are closely associated with the major events such as coordinated central bank interventions and the financial crises. 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. That is, dynamic market conditions govern the degree of efficiency of foreign exchange markets.

Acknowledgments

We would like to thank the two anonymous referees for the constructive comments that substantially improved the paper. The R package “vrtest” (version 0.95, freely available from http://www.r-project.org/) contains the functions for all tests analyzed in this paper.

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[13] We thank a referee for suggesting this point. We note that the validity of the binomial distribution depends on the independence of p-values over time, which might be questionable, as the referee pointed out.

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