Applied Financial Economics, 2011, **21**, 1409–1421

Routledge
Taylor & Francis Group

Nonlinear mean-reversion in Southeast Asian real exchange rates

Doo-Yull Choi[a], Bong-Han Kim[b,*] and See-Won Kim[c]

[a]*Department of Industrial Management, Korea University of Technology and Education, Chenan, Republic of Korea*
[b]*Department of International Economics, Kongju National University, Kongju, Republic of Korea*
[c]*Department of Economics, Chonnam National University, Gwangju, Republic of Korea*

We find nonlinear mean reverting tendencies in Southeast Asian currencies by applying the newly developed nonlinear unit-root test by Park and Shintani (2005). First, with the US dollar as the numeraire currency, we find that 63% of the real exchange rates of Southeast Asian currencies turn out to be stationary. However, with the Japanese yen as the numeraire currency, we find no evidence in favour of Purchasing Power Parity (PPP) for most currencies in Southeast Asia, except for the Korean won and Taiwanese dollar. These findings imply that Southeast Asian currencies may not form a yen-dominated Asian exchange rate system. Second, when the dollar-based real exchange rates of Southeast Asian countries are nonlinear mean reverting, we find that the mean-reverting process could be well described by the Exponential Smooth Transition Autoregressive (ESTAR) model, rather than the Double Threshold Autoregressive (DTAR) or Double Logistic Smooth Transition Autoregressive (DLSTAR) model. Our results are reinforced by impulse response function and forecasting analysis.

Keywords: purchasing power parity; nonlinear unit root test; Asian real exchange rates; dollar and yen

JEL Classification: F31; F41

I. Introduction

Based on Purchasing Power Parity (PPP), a common basket of goods and services denoted in the same currency costs the same across all countries. However, little consensus exists on the validity of PPP in the literature because the results depend on several factors, such as the econometric methodologies used, the assumptions on the market structure, the length of data span, numeraire currencies and the coverage of fixed exchange rate periods. For example, different econometric tools give conflicting test results. The Augmented Dickey–Fuller (ADF) unit root test tends to reject the PPP hypothesis, while the panel unit root test is inclined to support the PPP hypothesis. Another approach to the test of PPP lies in allowing for nonlinear dynamics in real exchange rate adjustment and, in sum, it offers

*Corresponding author. E-mail: bongkim@kongju.ac.kr

Applied Financial Economics ISSN 0960–3107 print/ISSN 1466–4305 online
http://www.informaworld.com
DOI: 10.1080/09603107.2011.572851

some resolution of the empirical anomalies of PPP theory.[1]

PPP has special meaning for Southeast Asian countries because the validity of PPP can be employed as a useful tool to identify the optimal common currency for the potential currency union among Southeast Asian countries. Most studies consider the US dollar, Japanese yen and Euro as potential candidates for the common currency in this region. The degree of conformity to the PPP can be one of the most useful criteria for examining the relationship between the candidate currency and the currencies of other East Asian countries. Although several empirical studies have tested the validity of the PPP of eastern Asian currencies in terms of the US dollar and Japanese yen, the results have, unfortunately, been mixed.

This article is based on the premise that real exchange rates follow a nonlinear mean-reversion process to test the validity of the PPP of Southeast Asian real exchange rates. Park and Shintani (2005) propose a new nonlinear unit root test (hereafter the inf. *t*-test) with the alternative of various nonlinearity. Instead of the Taylor approximation of the alternative, their approach is based on the Sup-Wald type test approach of Caner and Hansen (2001). In addition, Park and Shintani's (2005) approach can be applied to most of the transition functions used in practice. This article follows the approach of Park and Shintani (2005) to determine whether Southeast Asian real exchange rates are nonlinear stationary.

The rest of this article is organized as follows. Section II reviews the literature on nonlinear models of real exchange rates and the PPP hypothesis test for Southeast Asian currencies. Next, Section III contains the nonlinear unit root tests, while Section IV presents the data and a discussion of the empirical results. Section V includes a summary and conclusions.

II. Literature Review

Nonlinear AR models

Some studies have employed the idea of nonlinear reversion in exchange rates. For example, Dumas (1992) and Secu *et al*. (1995) consider transaction costs and show that the adjustment of real exchange rates towards PPP is a nonlinear process. Market friction introduces a neutral band, within which deviations from PPP are left uncorrected, as they are not large enough to cover transaction costs. Only deviations outside the neutral range are arbitraged away. Hence, deviation from PPP follows a nonlinear process that is mean-reverting (Baum *et al*., 2001).

Studies by, for example, Michael *et al*. (1997), Baum *et al*. (2001) and Taylor *et al*. (2001) use nonlinear models, such as Smooth Transition Autoregressive (STAR) models, to model real exchange rates. They employ the linearity tests of Teräsvirta (1994) to show evidence of the nonlinear adjustment of real exchange rates. However, since the linearity test of Teräsvirta (1994) assumes that real exchange rates are stationary, and thus the rejection of linearity with the test does not necessarily imply nonlinear mean-reversion, a new test method is needed in which the null hypothesis is the unit root in real exchange rates and the alternative is nonlinear mean-reversion. If the data generating processes of real exchange rates are nonlinear stationary, a conventional unit root test, such as the ADF test, has lower power in detecting its mean-reverting tendency, since the alternative of the ADF test is misspecified.[2]

In response to such problems of the ADF test, Kapetanios *et al*. (2003, Kapetanios–Shin–Snell, henceforth KSS) develop a nonlinear unit root test for the null hypothesis of a unit root against an alternative of an Exponential STAR (ESTAR) model (henceforth, KSS test).[3] Liew *et al*. (2004) use the KSS test to test the nonlinear mean-reversion property of Asian real exchange rates, and reject the unit root in most cases.

However, the KSS test relies on Taylor approximation to derive the limiting distribution under the alternative hypothesis. The asymptotics of the KSS test are obtained by approximating a smooth transition function with a first-order Taylor expansion around the transition parameter that governs the speed of transition. The accuracy of such an approximation may not be reliable for a nonstationary process, since higher order terms of the nonstationary process may remain nonnegligible.

Park and Shintani (2005) propose a inf. *t*-test with the alternative of various nonlinearity. Instead of the Taylor approximation of the alternative, their approach is based on the Sup-Wald type test approach of Caner and Hansen (2001). This article

[1] For the critical reviews on the PPP debate, see Sarno and Taylor (2002), Taylor and Taylor (2004) and Taylor (2006).

[2] Poor power performance of a standard linear unit-root test has been reported by many studies, including Balke and Fomby (1997), Enders and Granger (1998) and Taylor *et al*. (2001).

[3] Chortareas and Driver (2001) applied the KSS test to the real exchange rates for the Group of Seven (G7) countries and found nonlinear mean-reversion of the real rates of Japan, Germany and the UK.

Table 1. List of transition functions

Model	Transition function $\pi(x, \theta)$	Features
TAR: threshold AR	$1\{x \leq \mu\}$ where $1\{\cdot\}$ is an indicator function	An abrupt transition at a certain level, μ
LSTAR: logistic STAR	$[1+\exp\{\kappa(x-\mu)\}]^{-1}$	A smooth transition
ESTAR: exponential STAR	$1-\exp\{-\kappa^2(x-\mu)^2\}$	–
DTAR: doubly TAR, (three-regime TAR)	$1\{x \leq \mu_1\} + 1\{x \geq \mu_2\}$ where $\mu_1 \leq \mu_2$	A three-regime TAR model, symmetric around $(\mu_1+\mu_2)/2$
DLSTAR: doubly LSTAR (three-regime LSTAR)	$[1+\exp\{\kappa_1(x-\mu_1)\}]^{-1} + [1+\exp\{-\kappa_2(x-\mu_2)\}]^{-1}$ where $\mu_1 \leq \mu_2$	A three-regime STAR model

follows the approach of Park and Shintani (2005) to determine whether Southeast Asian real exchange rates are nonlinear stationary. Distinct features of their approach are as follows.

First, the framework of Park and Shintani (2005) is general enough to permit virtually all practically interesting transitional Autoregressive (AR) models with the threshold, discrete and smooth transition functions. Examples of such transition functions are given in Table 1.

Second, Park and Shintani (2005) propose the one-sided $\inf.t$-test instead of the two-sided tests that have been employed in the literature.[4] The one-sided test can effectively deal with the test of the null of a unit root against the alternative of a stationary transitional model. Last, Park and Shintani (2005) explicitly specify the parameter space to have a random limit and fully accounted for its variation in deriving their asymptotics under the null hypothesis. Since the parameters of the transitional AR models can only be identified under the alternative hypothesis, the parameter space is routinely set as a function of the data. Such a parameter space under the null of a unit root has a random limit, even under appropriate normalization. Hence, the null asymptotics are expected to be dependent upon the limit of the random parameter space. This dependency on the limit parameter space of the asymptotic critical values has never been properly acknowledged in the literature.

Under a general and realistic setup, Park and Shintani (2005) derive the full asymptotics for the transitional AR models under the unit root hypothesis. In particular, they show that the test has a well-defined limit distribution that is free of any nuisance parameters and depends only on the type of transition functions and the limit parameter space. They provide the critical values of the tests for the commonly used transitional AR models, so that neither simulation nor bootstrap is necessary to calculate the critical values. Examples include the Threshold Autoregressive (TAR) model, Logistic Smooth Transition Autoregressive (LSTAR) model, ESTAR model and their extensions, such as the Double TAR (DTAR) and Double LSTAR (DLSTAR) models.

Southeast Asian real exchange rates

Recently, some studies have examined the validity of PPP theory for Asian economies as their importance has increased both in international trade and international financial market.[5] Most empirical studies based on a conventional ADF test have failed to reject the unit-root hypothesis of the real exchange rates of Asian currencies (Wu *et al.*, 2004). Hence, recent studies have tried to employ more sophisticated econometric methodologies, such as panel unit root tests, unit root tests with structural breaks and the nonlinear unit root test. For instance, Basher and Mohsin (2004) apply the Pedroni (1999) panel

[4] Widely used current tests and asymptotics for a unit root test against alternative AR models are not comparable to Park and Shintani's (2005), in that they cover only very limited transitional AR models as alternatives under more restrictive conditions. For example, the test of KSS (2003) is based on the Taylor approximation of the transition function, which requires a totally different asymptotic analysis. They obtain the null asymptotics under the assumption of a fixed compact parameter space, resulting in a null distribution that is degenerate with respect to the threshold parameter. Other examples of this approach include KSS (2003), Seo (2003), Bec *et al.* (2004), and Bec *et al.* (2009), all of whom study the unit-root test in the DTAR model. Their null asymptotics are derived under more restrictive conditions and thus have limited practical relevancy. For example, KSS (2003) and Seo (2003) assume that the limit of the normalized parameter space is nonrandom and compact.

[5] There also exist studies examining the empirical validity of the theory for non-Asian developing countries; for instance, Alves *et al.* (2001) for Brazil, Ghoshroy-Saha and Berg (1996) for Mexico and Nagayasu (2002) and Chang *et al.* (2006) for African countries.

cointegration test for ten Asian developing countries and do not find any evidence of cointegration between nominal exchange rates and relative prices. Using a panel cointegration test that accommodates structural breaks, on the other hand, Narayan (2010) find some evidence of a panel cointegration for six Asian countries. Enders and Chumrusphonelert (2004) employs a threshold cointegration model and show that long-run PPP holds for most Asian countries when Japan and USA are used as base countries.

An animated discussion is taking place on the feasibility of a currency union for East Asian countries. One of the most important issues within the debate is what currency to use as the common currency. Several studies have considered the US dollar and Japanese yen as potential candidates for the common currency.[6] Depending upon the criteria used, conflicting results have been attained. The degree of conformity to PPP can be a useful tool to examine the relationship between the candidate currency and the currencies of other East Asian countries. Hence, several studies have tested the validity of the PPP of East Asian currencies in terms of the US dollar and Japanese yen. However, little consensus exists on the validity of PPP for East Asian currencies because the results depend on several factors, such as the econometric methodologies used and the length of the period under study.

The following studies have provided evidence for the validity of the PPP hypothesis in terms of the Japanese yen. Aggarwal *et al.* (2000) obtain some results supporting the PPP hypothesis in bilateral real exchange rates between the Japanese yen and some Southeast Asian economies when changes in the mean of the real exchange rates were allowed. Aggarwal *et al.* (2000) find that evidence for PPP was weaker for Asian exchange rates with the US dollar. However, their results are strongly dependent on the presence of structural breaks. Aggarwal *et al.* (2000) assert that their results suggest the existence of Asian countries whose economies are highly interconnected with that of Japan, and also state that Southeast Asian currencies may be forming a yen-dominated Asian exchange rate system. Azali *et al.* (2001) use the Im, Pesaran and Shin (IPS, 1996) panel unit root test and Pedroni's (1995) panel cointegration test of the PPP hypothesis for seven developing economies in Asia, and find evidence in favour of PPP between Japan and these countries.

However, some studies have supported the PPP hypothesis with respect to the bilateral Southeast Asian currencies relative to the US dollar. Wu *et al.* (2004) show that conventional panel unit root tests fail to reject the unit root hypothesis of Southeast Asian real exchange rates in terms of the US dollar. However, when they use the panel unit root test with a break in mean, Wu *et al.* (2004) find that, in terms of the US dollar, Southeast Asian real exchange rates are stationary. Kim *et al.* (2009) use a time-varying coefficient cointegration model to test for PPP of Southeast Asian currencies and to track changes in purchasing power relationships over time. They find the instability of the relationship between exchange rates and price differentials. When the cointegration vector is allowed to vary with time, they find evidence of a cointegration relationship for four countries in terms of the US dollar and for four countries in terms of the Japanese yen.

Liew *et al.* (2004) apply the KSS test to 11 Asian real exchange rates and rejected the unit-root hypothesis in eight US dollar-based and six Japanese yen-based rates. From this result, Liew *et al.* (2004) suggest that price levels in Asian countries adjust slightly more closely towards the US price level compared to that of Japan, possibly because the influence of the US economy is more dominant in terms of a trading partner.

III. Nonlinear Unit Root Test of Park and Shintani

Park and Shintani (2005) propose a test of the unit root under the null of the unit root against an alternative of the nonlinear mean-reversion model, which includes a wide range of AR models with threshold, discrete and smooth transition functions.[7]

Consider an AR model,

$$\Delta y_t = \lambda(\theta)\, y_{t-1}\pi(y_{t-d},\theta) + \sum_{i=1}^{p} \alpha_i \Delta y_{t-i} + \varepsilon_t \qquad (1)$$

where y_{t-d} is the transition variable with delay lag $d \geq 1$, θ an m-dimensional parameter vector in the transition function, and can be identified only under the alternative hypothesis of stationarity and π a real-valued transition function on $R\times R^m$. Since the regression model in Equation 1 can represent a broad class of nonlinear mean-reverting AR models with a relevant choice of transition functions, the test

[6] Some studies have provided evidence of a 'yen block' by showing the cointegration relationship between the Japanese yen and Southeast Asian countries (Aggarwal and Mougoue, 1996; Tse and Ng, 1997).
[7] For details of the test procedure, the reader is referred to their original work.

is claimed to be useful in identifying the existence of the unit root in diverse nonlinear AR models.

Testing the unit-root null hypothesis is equivalent to testing $H_0 : \lambda = 0$ against $H_1 : \lambda < 0$, which involves estimating λ in Equation 1 using least squares for each possible value of the transition parameter $\theta \in \Theta_n$ to obtain the following *t*-ratio

$$T_n(\theta) = \frac{\hat{\lambda}_n(\theta)}{s(\hat{\lambda}_n(\theta)} \tag{2}$$

where $s(\hat{\lambda}_n(\theta))$ is the SE of the estimate $\hat{\lambda}_n(\theta)$. The inf. *t*-test statistic is then defined as

$$T_n = \inf_{\theta \in \Theta_n} T_n(\theta) \tag{3}$$

which is the infinum of *t*-ratios in Equation 3 taken over all possible values of $\theta \in \Theta_n$, where Θ_n is a random sequence of parameter spaces given for each n as functions of the sample $(y_1, \ldots, y_n)$. The limit distribution of the inf. *t*-statistic is free from any nuisance parameters and depends only on the transition function and the limit parameter space.

Among the nonlinear mean-reverting alternative models, we focus on the TAR and stationary STAR models, which are frequently employed in empirical studies. If y_t follows the unit root inside bands and shows mean-reversion when it deviates from the bands, y_t can be captured by the TAR model. However, if the mean-reversion occurs smoothly and the speed of adjustment depends on the size of the deviation from the mean, then y_t can be well described by the STAR process.

For the STAR model, y_t is assumed to be a nonstationary process but the speed of mean-reversion increases with the size of deviation. The Data Generation Process (DGP) of y_t can be described as the weighted sum of stationary and nonstationary models with the weight of the transition function, $\pi(y_{t-d}, \theta)$,

$$y_t = [1 - \pi(y_{t-d}, \theta)]\, y_{t-1} + \pi(y_{t-d}, \theta)\rho y_{t-1} + u_t \tag{4}$$

With an exponential transition function, ADF type expression of the above equation becomes

$$\Delta y_t = (\rho - 1)(y_{t-1} - \mu_y)[1 - \exp\{-\kappa^2(y_{t-d} - \mu_y)^2\}] + \sum_{i=1}^{p} \alpha_i \Delta y_{t-i} + u_t \tag{5}$$

where the transition function $[1 - \exp\{-\kappa^2 (y_{t-d} - \mu_y)^2\}]$ captures the degree of mean-reversion. The parameter μ_y denotes the mean value of y_t and the parameter κ determines the speed of adjustment. The exponential transition function takes a value between 0 and 1 and is symmetric around 0. It is 0 when y_t is equal to its mean value and it becomes 1 as the deviation of y_t becomes infinity.

IV. Empirical Investigation

Data description

We tested PPP for the real exchange rates of Southeast Asian Countries from January 1975 to December 2004 using monthly data[8] from International Monetary Funds (IMF's) International Financial Statistics.[9] The domestic- and foreign-price series are based on the consumer price index. The Southeast Asian countries selected as home countries were Hong Kong, Indonesia, Korea, Malaysia, the Philippines, Singapore, Taiwan and Thailand. The US and Japan were chosen as the foreign countries.

The real exchange rate, y_t, is constructed by $y_t = \ln S_t + \ln P_t^* - \ln P_t$, where S_t is the nominal exchange rate defined as the price of foreign currency in terms of home currency, P_t the domestic price level and P_t^* the price level of the foreign country.

The behaviour of the Southeast Asian real exchange rates in terms of the US dollar can be found in Fig. 1. As Wu *et al.* (2004) indicate, the real exchange rates of Southeast Asian currencies in terms of the US dollar appear to be subject to several structural changes.

We may conjecture that regime shifts in these real rates took place due to both the Plaza Accord in 1985 and the Asian currency crisis in 1997.[10] Except for Indonesia and Malaysia, the Plaza accord had resulted in the persistent devaluation of exchange rates in Southeast Asian countries. In addition, the outbreak of the Asian currency crisis in 1997 caused a sharp real devaluation of the currencies of Hong Kong, Indonesia, Korea, Malaysia, the Philippines, Singapore and Thailand.

Figure 2 presents the behaviour of the real exchange rates of the Southeast Asian countries in terms of the Japanese yen.

As shown in Fig. 2, the time series behaviour of yen-denominated real exchange rates shows an increasing trend, except for Hong Kong and Korea.

[8] Because of the availability of data, the sample period for Hong Kong is from January 1976 to December 2004.
[9] Data for Taiwan were obtained from DataStream.
[10] The simulation study by Choi and Moh (2007) shows that inf. *t*-test of Park and Shintani (2005) exhibits decent discriminatory power for the null of stationarity with one break against unit-root while the ADF test does not.

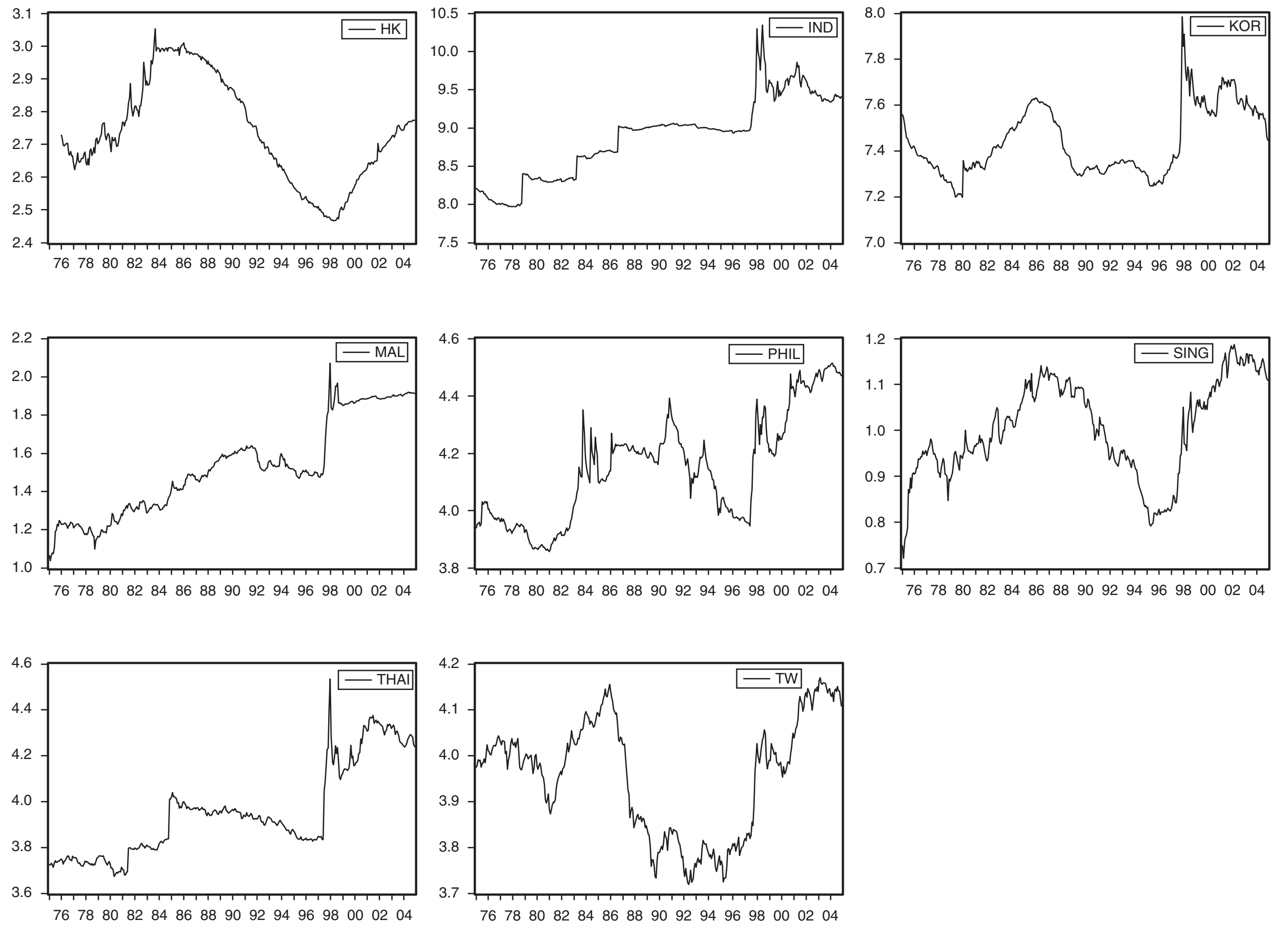

Fig. 1. Real exchange rates in terms of US dollar

The presence of the trend implies a persistent appreciation of the Japanese yen against other Asian currencies.

Nonlinear unit root tests

The unit root test results are summarized in Tables 2 and 3. The results in Tables 2 and 3 show that the ADF test fails to reject the null of a unit root except for one case,[11] implying that the real exchange rates of Southeast Asian countries do not have mean-reverting tendencies. We conducted nonlinear unit root tests with three different alternatives: ESTAR (6), DTAR (7) and DLTAR (8) models.

$$\Delta y_t = \lambda(y_{t-1} - v)[1 - \exp\{-\kappa^2(y_{t-d} - v)^2\}] + \sum_{k=1}^{p} \alpha_k \Delta y_{t-k} + \varepsilon_t \tag{6}$$

$$\Delta y_t = \lambda[(y_{t-1} - v_1)1\{y_{t-d} \leq \mu_1\} + (y_{t-1} - v_2)1\{y_{t-d} \geq \mu_2\}] + \sum_{k=1}^{p} \alpha_k \Delta y_{t-k} + \varepsilon_t \tag{7}$$

$$\Delta y_t = \lambda\left(\frac{y_{t-1} - v_1}{1 + e^{\kappa(y_{t-d} - \mu_1)}} + \frac{y_{t-1} - v_2}{1 + e^{-\kappa(y_{t-d} - \mu_2)}}\right) + \sum_{k=1}^{p} \alpha_k \Delta y_{t-k} + \varepsilon_t \tag{8}$$

As Tables 2 and 3 report, the null of a unit root is rejected against the ESTAR alternative for the US dollar-denominated real exchange rates of five countries: Indonesia, Korea, Malaysia, Singapore and Thailand. For Japanese yen-denominated real exchange rates, the null of a unit root is rejected for two countries: Korea and Taiwan. Tables 2 and 3 show that the null of a unit root is rejected against the DTAR alternative for the US dollar-denominated

[11] ADF test with a time trend rejects the unit-root for Indonesian real exchange rate in terms of the US dollar.

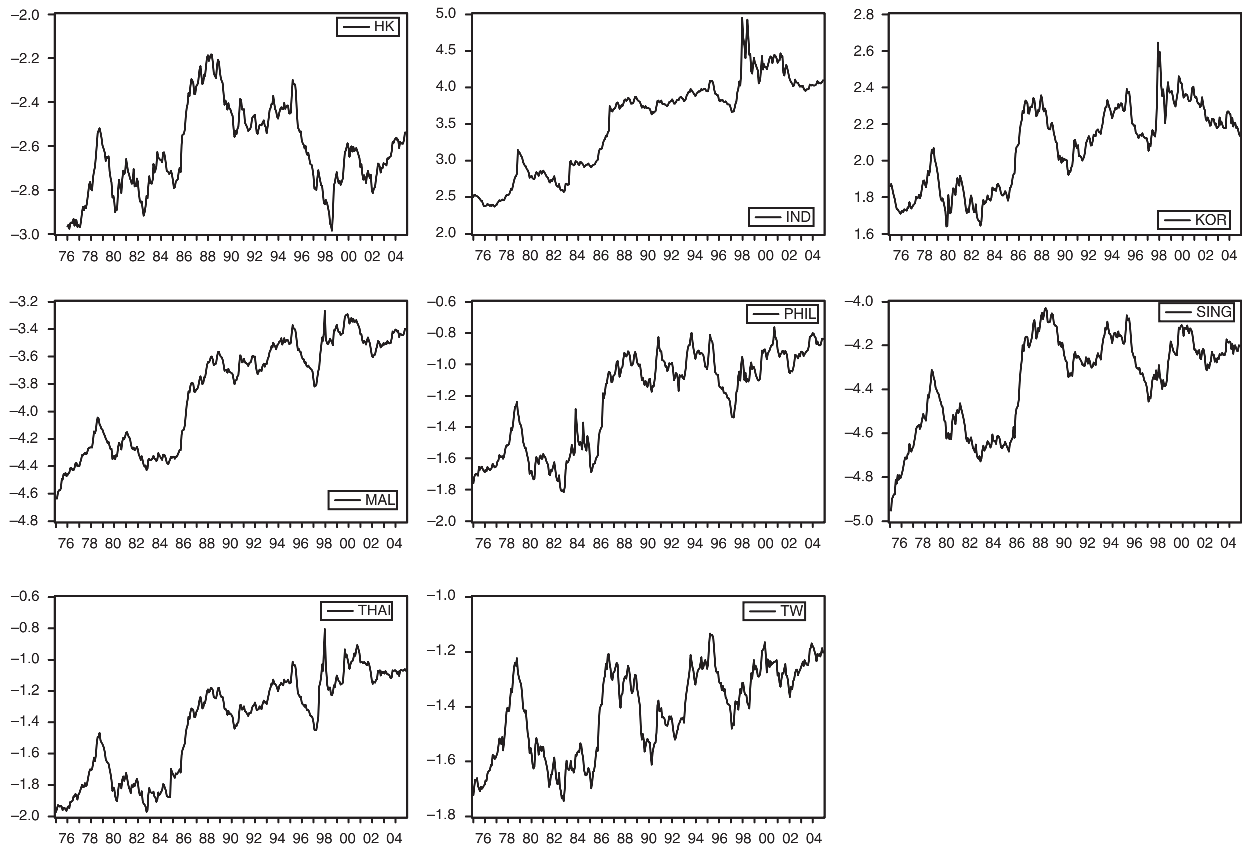

Fig. 2. Real exchange rates in terms of Japanese yen

Table 2. Nonlinear unit root test of dollar based rates

	ADF − μ	ADF − γ	inf.t : ESTAR	inf.t : DTAR	inf.t : DLSTAR
Hong Kong	−0.822 (−2.928)	−0.861 (−3.440)	−1.158 (−2.27)	−1.040 (−2.71)	−1.067 (−2.70)
Indonesia	−1.475 (−2.901)	−3.470* (−3.441)	−4.410* (−2.27)	−3.047* (−2.71)	−3.282* (−2.70)
Korea	−2.193 (−2.878)	−2.637 (−3.409)	−6.483* (−2.27)	−2.808* (−2.71)	−2.934* (−2.70)
Malaysia	−1.315 (−2.886)	−2.840 (−3.399)	−3.739* (−2.27)	−2.889* (−2.71)	−3.440* (−2.70)
Philippines	−1.148 (−2.889)	−2.223 (−3.395)	−1.557 (−2.27)	−0.873 (−2.71)	−1.217 (−2.70)
Singapore	−2.574 (−2.887)	−2.372 (−3.402)	−3.455* (−2.27)	−3.174* (−2.71)	−3.178* (−2.70)
Thailand	−1.410 (−2.880)	−2.906 (−3.407)	−4.064* (−2.27)	−2.192 (−2.71)	−2.361 (−2.70)
Taiwan	−1.166 (−2.893)	−1.159 (−3.450)	−1.875 (−2.27)	−1.556 (−2.71)	−1.577 (−2.70)

Notes: The delay parameter d was chosen by the partial autocorrelation rule following Granger and Teräsvirta (1993). Lag length p are set to be 1. ADF − μ and ADF − γ are ADF test-statistics with an intercept and time trend, respectively. Size-corrected 5% critical values are given in parentheses.
* Denotes significance at the 5% level.

real exchange rates of Indonesia, Korea, Malaysia and Singapore, and for the Japanese yen-denominated real exchange rate of Korea. Tables 2 and 3 report that when the DLSTAR model is used as the alternative, the null of a unit root is rejected for the US dollar-based real exchange rates of Indonesia, Korea, Malaysia and Singapore, and for all Japanese yen-based rates of Korea and Taiwan.

Based on the test results, we note the following empirical findings. First, when the Japanese yen is used as the numeraire currency, the Korean won and Taiwanese dollar are found to be stationary. About 63% of the real exchange rates are stationary when

Table 3. Nonlinear unit root test of Japanese yen-based rates

	ADF $-\ \mu$	ADF $-\ \gamma$	inf. t : ESTAR	inf. t : DTAR	inf. t : DLSTAR
Hong Kong	−2.289 (−2.901)	−2.206 (−3.391)	−2.161 (−2.27)	−2.382 (−2.71)	−2.397 (−2.70)
Indonesia	−2.113 (−2.897)	−1.643 (−3.436)	−1.142 (−2.27)	−2.036 (−2.71)	−2.069 (−2.70)
Korea	−2.165 (−2.901)	−1.866 (−3.441)	−4.173* (−2.27)	−2.879* (−2.71)	−3.026* (−2.70)
Malaysia	−1.774 (−2.897)	−1.206 (−3.434)	−1.742 (−2.27)	−1.604 (−2.71)	−1.697 (−2.70)
Philippines	−2.179 (−2.897)	−1.933 (−3.435)	−1.882 (−2.27)	−1.945 (−2.71)	−2.064 (−2.70)
Singapore	−2.016 (−2.289)	−1.868 (−3.435)	−2.141 (−2.27)	−1.783 (−2.71)	−2.022 (−2.70)
Thailand	−2.080 (−2.896)	−1.824 (−3.440)	−2.114 (−2.27)	−2.042 (−2.71)	−2.052 (−2.70)
Taiwan	−2.757 (−2.892)	−3.144 (−3.454)	−3.472* (−2.27)	−2.697 (−2.71)	−2.712* (−2.70)

Notes: The delay parameter d was chosen by the partial autocorrelation rule following Granger and Teräsvirta (1993). Lag length p are set to be 1. ADF $-\ \mu$ and ADF $-\ \gamma$ are ADF test-statistics with an intercept and time trend, respectively. Size-corrected 5% critical values are given in parentheses.
* Denotes significance at the 5% level.

the US dollar is the numeraire currency. This result is consistent with Liew *et al.* (2004), who find that two-thirds of the US dollar-based real rates are nonlinear stationary processes and 60% of the Japanese yen-based real rates are nonlinear stationary processes using the KSS test. Second, when the US dollar-based real exchange rates of Southeast Asian countries are nonlinear mean-reverting, the mean-reverting process can be well described by the ESTAR model, rather than the DTAR or DLSTAR model.

Threshold models, including DTAR and DLSTAR, allow for a neutral band within which no adjustment takes place, so that real exchange rates may exhibit unit root behaviour, while outside the band, the real exchange rate switches abruptly to become a stationary process. However, the ESTAR model shows smooth, rather than single-threshold or discrete, nonlinear movement of the real exchange rate towards its equilibrium value. Hence, the nonlinear unit root test result implies smooth nonlinear mean-reversion behaviour of US dollar based Southeast Asian real exchange rates.

In short, we found strong evidence in favour of PPP for most Southeast Asian currencies in terms of the US dollar. However, if the Japanese yen is used as the numeraire currency, the evidence for PPP turns out to be much weaker for Southeast Asian exchange rates. It seems that more clear and obvious results are needed to support the idea that Southeast Asian currencies may be forming an Asian exchange rate system in which the common currency is the Japanese yen, as some have insisted (Aggarwal *et al.*, 2000).

Impulse response function

The mean-reverting properties of the estimated nonlinear model can be reaffirmed through the impulse response function analysis. The impulse response function records the effect of a shock at time t on the model at time $t+j$. The impulse response function of a linear model is invariant with respect to the initial conditions, the future disturbances and the size of shocks. With nonlinear models, the shape of the impulse response function depends upon either the history of the system at the time the shock took place, the size of the shock considered or the distribution of future exogenous innovations.

Following Gallant *et al.* (1993), we estimate the impulse response functions by Monte Carlo simulations as follows.[12] Starting at period three in the sample (i.e. March 1975), current and lagged values are set to the actual historical values of the real exchange rates.[13] Using the estimated ESTAR model, which is given in Table 4, our Monte Carlo simulations generate 200 data sets of length 200, with and without a shock of size s at time t, and realizations of the difference between the two simulated paths are calculated. We then move up one data point, that is, set t equal to April 1975, and repeat this procedure.

Once this is performed for every data point from March 1975 to December 2004, an average over all the simulated sequences, with and without the shock s at time t, is taken as the estimated impulse response function conditional on the average history of the given series and for a given shock size.

[12] Gallant *et al.* (1993) define the impulse response function as a sequence of values defined over T-periods, $\{I[1,s,h], I[2,s,h], \ldots, I[T,s,h]\}$. It represents the difference between the path of y which is expected to prevail as time $t+1$ through $t+T$ following an additive shock of size$s$ at time t and the path without shock at time t, each conditioned on the history of the system at time t, $h(t)$; $I[j, s(t), h(t)] \equiv E[y(t+j)|s(t), h(t)] - E[y(t+j)|h(t)]$, $j = 1, 2, \ldots, T$.
[13] Hence, we set $t =$ March 1975, $t-1 =$ February 1975, and $t-2 =$ January 1975.

Table 4. Estimation results of the ESTAR model $\Delta y_t = \lambda(y_{t-1} - \nu)[1 - \exp\{-\kappa^2(y_{t-d} - \nu)^2\}] + \sum_{k=1}^{p} \alpha_k \Delta y_{t-k} + \varepsilon_t$

	US dollar based			Japanese yen based		
	λ	ν	κ	λ	ν	κ
Hong Kong	−0.2416	2.7159	0.6376	−0.0364	−2.5622	4.0147
Indonesia	−0.9869	8.7658	0.1929	−0.2113	3.4289	0.4523
Korea	−0.3517	7.4574	1.8851	−0.2981	2.0499	1.2852
Malaysia	−0.8964	1.5600	0.4052	−0.2055	−3.9146	0.7832
Philippines	−0.0097	4.3333	11.6408	−0.2357	−1.2999	0.9674
Singapore	−0.9944	1.0152	0.9628	−0.1466	−4.3974	1.4932
Thailand	−0.9839	3.9404	0.4994	−0.2273	−1.4635	0.9449
Taiwan	−0.6082	3.9577	0.7841	−0.2555	−1.4414	1.8926

Notes: The delay parameter d was chosen by the partial autocorrelation rule following Granger and Teräsvirta (1993). Lag length p are set to be 1.

We used four sizes of shocks to y, that is, 30%, 10%, 5% and 1%, to compare the persistence of very large and very small shocks.[14] Figure 3 shows the estimated impulse response function based on estimated ESTAR models, which are reported in Table 4. The absolute value of the slope of the impulse response functions becomes steeper as the size of shock increases, which is the very characteristic of the nonlinear process. The persistence of the shocks also depends on the size of the transition parameter, κ, which governs the speed of transition. Since the estimate for the Indonesian rupiah/US dollar real rate is the lowest value at 0.1929, the shocks to the real rate decay at the lowest rate.

Forecasting analysis

Another method of judging the appropriateness of the nonlinear mean-reversion model is to test the out-of-sample predictability. To compare the out-of-sample forecast accuracy of the ESTAR model with a random walk model, we employ the Root Mean Square Errors (RMSE) statistic. We obtain the forecast errors through a recursive estimation of out-of-sample dynamics up to $k = 3$, 6, 9 and 12 months ahead over the period from 1990 to 2004.

To test the null hypothesis that the forecasts from the random walk and the ESTAR models are equally accurate, we use Diebold and Mariano's (1995) test-statistic. As given in Table 5, the forecasts generated by the ESTAR model beat the random walk model at the 6-, 9- and 12-month horizons for rupiah/US dollar, won/US dollar, won/Japanese yen and Taiwan dollar/Japanese yen. Moreover, the forecast accuracy increases sharply as the forecast horizon grows. However, as can be expected, the random walk model has lower RMSE than the ESTAR model for all currencies considered at a 3-month horizon. These results may imply that in the short-run, the ESTAR model cannot fully catch the dynamics of Asian real exchange rates. However, as the time span grows beyond 3 months, the ability of the ESTAR model to describe the Asian real exchange rate movement increases sharply.

V. Conclusion

PPP has a special meaning to Southeast Asian countries because its validity can be employed as a useful tool to select the optimal common currency for the currency union among Southeast Asian countries. Although several empirical studies have tested the validity of the PPP of Southeast Asian currencies in terms of the US dollar and Japanese yen, the results have been mixed. Little consensus exists on the validity of PPP in the literature because the results depend on several factors, such as the econometric methodologies used, the length of data span, numeraire currencies and the coverage of fixed exchange rate periods. This article is based on the premise that real exchange rates follow a nonlinear mean-reversion process to test the validity of the PPP of Southeast Asian real exchange rates. The literature shows mixed results on the validity of PPP because conventional unit root tests, such as the ADF test, have lower power in detecting the nonlinear mean-reverting tendency as a result of misspecified alternatives. To overcome these problems, we use a comprehensive nonlinear unit root test developed by Park and Shintani (2005).

[14] A shock of k percent to the level of y_t involves augmenting y_t additively by $s_t = \log(1 + k/100)$.

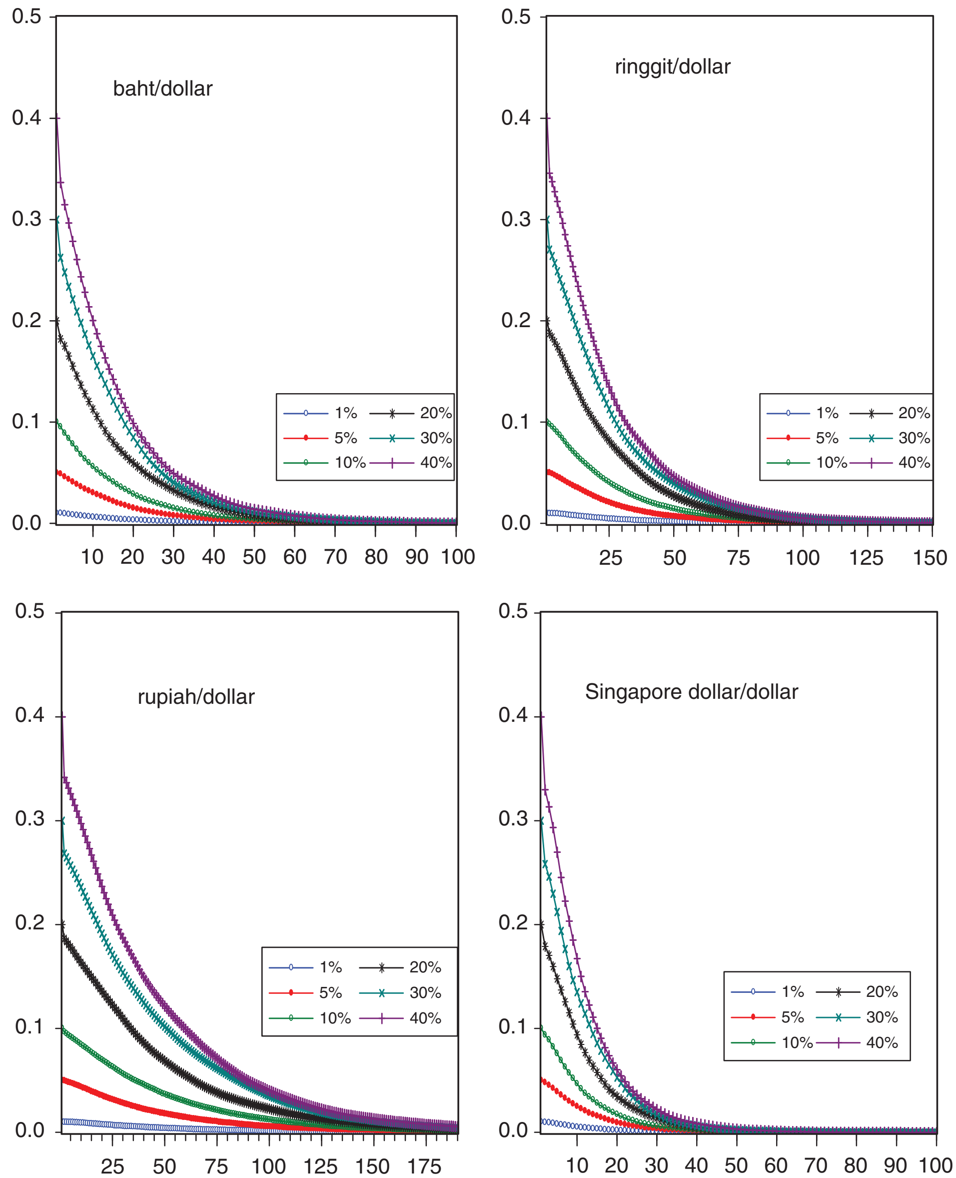

Fig. 3. Impulse response function of estimated ESTAR models

We obtained the following main empirical findings. First, 63% of the real exchange rates are stationary with the US dollar as the numeraire currency. When the Japanese yen is used as the numeraire currency, the Korean won and Taiwan dollar are stationary. This result is consistent with Liew *et al.* (2004), who use the KSS test and claim that two-thirds of the US dollar-based real rates are nonlinear stationary processes and 60% of the Japanese yen-based real rates are nonlinear stationary processes. Second, when the dollar-based real exchange rates of Southeast Asian countries are nonlinear mean-reverting, the mean-reverting process can be well described by the ESTAR model, instead of the DTAR or DLSTAR model. Threshold models, including DTAR and DLSTAR, allow for a neutral band (inner regime) within which no adjustment takes place, so that real exchange rates may exhibit unit root behaviour, while outside the band (outer two regimes), the real exchange rates switch abruptly to become stationary processes.

However, unlike the single threshold or discrete model, the ESTAR model shows smooth nonlinear movements, instead of abrupt changes, towards its equilibrium value in the outer two regimes and unit root behaviour in its inner regime.

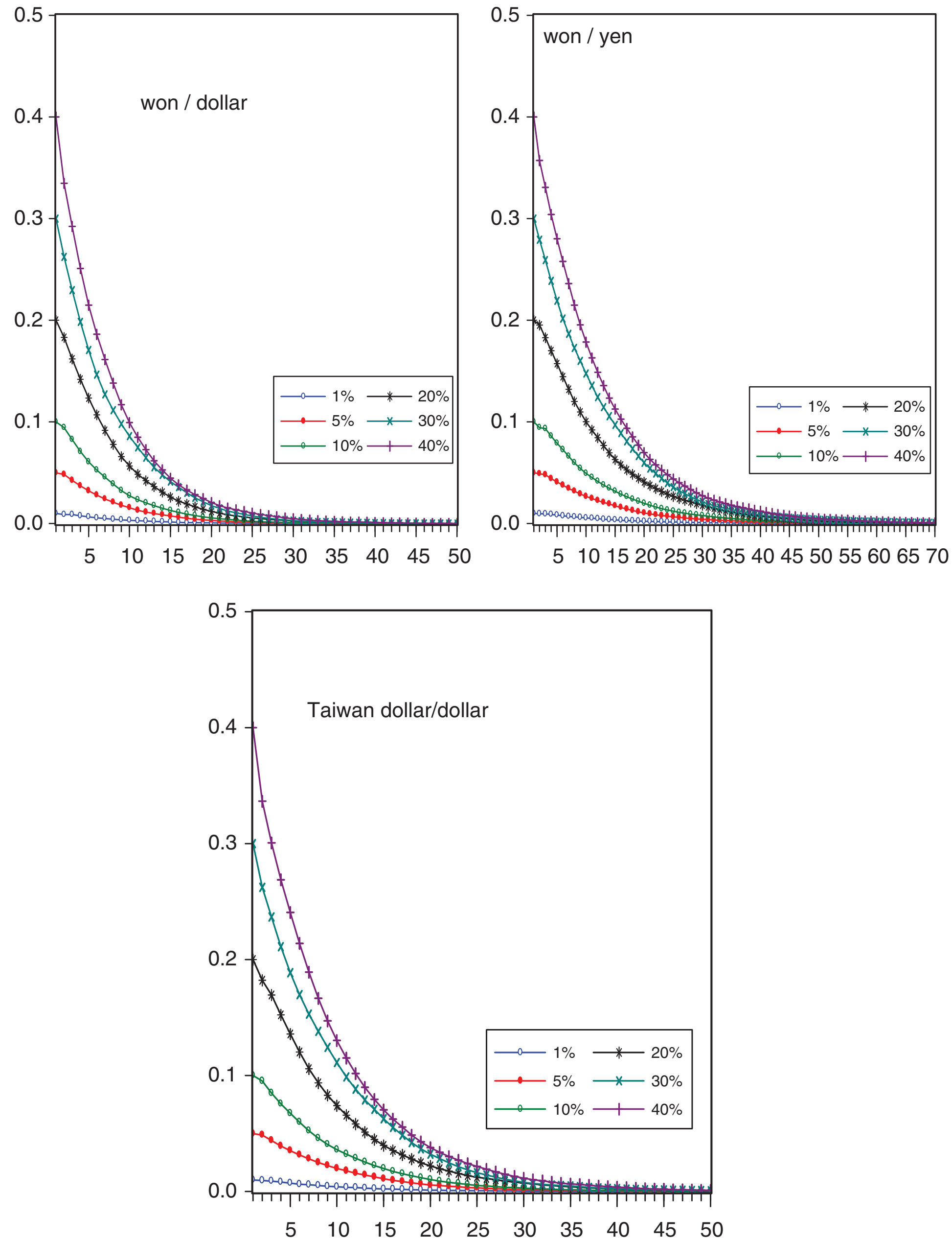

Fig. 3. Continued

Hence, from our nonlinear unit root test results, we can state that the US dollar-based Southeast Asian real exchange rates move smoothly towards their equilibrium values with nonlinear mean-reverting behaviours.

The validity of the ESTAR model is also supported by comparing the out-of-sample forecast performance with a random walk model. In the short-run, the ESTAR model does not beat the random walk model. However, as the forecast horizon grows, the ESTAR model by far outperforms the random walk model.

In addition, we did not find any evidence in favour of PPP for most Southeast Asian currencies in terms of the Japanese yen. We need more clear and obvious results before supporting the idea that Southeast Asian currencies may be forming an Asian exchange rate system in which the common currency is Japanese yen, as has been insisted in some studies (Aggarwal *et al.*, 2000).

Table 5. Forecasting analysis results

	Forecasting horizon							
	3 months		6 months		9 months		12 months	
	OUT/RW	DM	OUT/RW	DM	OUT/RW	DM	OUT/RW	DM
US dollar based								
Indonesia	1.002	0.0477 (0.519)	0.8119	−1.3850 (0.083)	0.6797	−2.0198 (0.021)	0.6505	−2.0023 (0.022)
Korea	0.9629	−1.0403 (0.149)	0.7673	−1.6437 (0.050)	0.6936	−2.0382 (0.020)	0.6231	−2.4770 (0.006)
Malaysia	1.0878	2.0806 (0.981)	0.8469	−0.7129 (0.237)	0.7680	−1.0850 (0.138)	0.7264	−1.3421 (0.089)
Singapore	1.0635	1.3869 (0.917)	0.8960	−0.9245 (0.177)	0.7768	−1.9583 (0.025)	0.6874	−2.2872 (0.011)
Thailand	2.3874	1.0586 (0.855)	1.4129	0.9995 (0.841)	1.4376	0.9010 (0.802)	1.4962	0.8514 (0.796)
Japanese yen based								
Korea	0.9669	−0.6961 (0.243)	0.7893	−1.9600 (0.024)	0.7989	−1.9101 (0.028)	0.7694	−2.0583 (0.019)
Taiwan	1.0135	0.4715 (0.681)	0.7405	−2.9173 (0.002)	0.7055	−2.5237 (0.006)	0.6555	−2.8282 (0.002)

Notes: DM denotes Diebold−Mariano-statistics. Figures in parentheses denote the p-value of DM's-statistic. OUT and RW are RMSE of ESTAR model and random walk model, respectively.

Acknowledgement

The author is very grateful to Joon Y Park for helpful discussions and comments.

References

Aggarwal, R., Montanes, A. and Ponz, M. (2000) Evidence of long-run purchasing power parity: analysis of real Asian exchange rates in terms of the Japanese yen, *Japan and the World Economy*, **12**, 351–61.

Aggarwal, R. and Mougoue, M. (1996) Cointegration among Asian currencies: evidence of the increasing influence of the Japanese yen, *Japan and the World Economy*, **8**, 291–308.

Alves, D. C. O., Cati, R. C. and Fava, V. L. (2001) Purchasing power parity in Brazil: a test for fractional cointegration, *Applied Economics*, **33**, 1175–85.

Azali, M., Habibullah, M. S. and Baharumshah, A. Z. (2001) Does PPP hold between Asian and Japanese economies? Evidence using panel unit root and panel cointegration, *Japan and the World Economy*, **13**, 35–50.

Balke, N. and Fomby, T. (1997) Threshold cointegration, *International Economic Review*, **38**, 627–45.

Basher, S. A. and Mohsin, M. (2004) PPP tests in cointegrated panels: evidence from Asian developing countries, *Applied Economics Letters*, **11**, 163–6.

Baum, C. F., Barkoulas, J. T. and Caglayan, M. (2001) Nonlinear adjustment to purchasing power parity in the post-Bretton Woods era, *Journal of International Money and Finance*, **20**, 379–99.

Bec, F., Salem, M. B. and Carrasco, M. (2004) Tests for unit-root versus threshold specification with an Application to the Purchasing Power Parity Relationship, *Journal of Business and Economic Statistics*, **22**, 382–95.

Bec, F., Salem, M. B. and Carrasco, M. (2009) Detecting mean reversion in real exchange rates from a multiple regime STAR model, CIRANO Working Papers No. 2009s–18.

Caner, M. and Hansen, B. E. (2001) Threshold autoregression with a unit root, *Econometrica*, **69**, 1555–96.

Chang, T., Change, H. L., Chu, H. P. and Su, C. W. (2006) Does PPP hold in African countries? Further evidence based on a highly dynamic non-linear (logistic) unit root test, *Applied Economics*, **38**, 2453–9.

Choi, C. Y. and Moh, Y. K. (2007) How useful are tests for unit-root in distinguishing unit-root processes from stationary but non-linear processes?, *Econometric Journal*, **10**, 82–112.

Chortareas, G. E. and Driver, R. L. (2001) PPP and the real exchange rate-real interest rate differential puzzle revisited: evidence from nonstationary panel data, Working Paper No. 138, University of Exeter, Bank of England.

Diebold, F. and Mariano, R. (1995) Comparing predictive accuracy, *Journal of Business and Economic Statistics*, **13**, 253–62.

Dumas, B. (1992) Dynamic equilibrium and the real exchange rate in a spatially separated world, *Review of Financial Studies*, **5**, 153–80.

Enders, W. and Chumrusphonelert, K. (2004) Threshold cointegration and purchasing power parity in the Pacific nations, *Applied Economics*, **36**, 889–96.

Enders, W. and Granger, C. W. J. (1998) Unit root tests and asymmetric adjustment with an example using the term structure of interest rate, *Journal of Business and Economic Statistics*, **16**, 304–11.

Gallant, R., Rossi, P. and Tauchen, G. (1993) Nonlinear dynamic structures, *Econometrica*, **61**, 871–907.

Ghoshroy-Saha, A. and Berg, H. V. D. (1996) Mexico's futile attempt to defy purchasing power parity, *Applied Economics Letters*, **3**, 395–9.

Granger, C. W. J. and Teräsvirta, T. (1993) *Modelling Nonlinear Economic Relationships*, Oxford University Press, Oxford.

Im, K. S., Pesaran, M. H. and Shin, Y. (IPS) (1996) Testing for unit roots in heterogeneous panels, *Journal of Econometrics*, **115**, 53–74.

Kapetanios, G., Shin, Y. and Snell, A. (KSS) (2003) Testing for a unit root in the nonlinear STAR framework, *Journal of Econometrics*, **112**, 359–79.

Kim, B. H., Kim, H. K. and Oh, K. Y. (2009) The purchasing power parity of Southeast Asian currencies: a time-varying coefficient approach, *Economic Modeling*, **26**, 96–106.

Liew, V. K., Baharumshah, A. Z. and Chong, T. T. (2004) Are Asian real exchange rates stationary?, *Economics Letters*, **83**, 313–16.

Michael, P., Nobay, A. R. and Peel, D. A. (1997) Transaction costs and nonlinear adjustment in real exchange rates: an empirical investigation, *Journal of Political Economy*, **105**, 862–79.

Nagayasu, J. (2002) Does the long-run PPP hypothesis hold for Africa? Evidence from a panel cointegration study, *Bulletin of Economic Research*, **542**, 181–7.

Narayan, P. K. (2010) Evidence on PPP for selected Asian countries from a panel cointegration test with structural breaks, *Applied Economics*, **42**, 325–32.

Park, J. Y. and Shintani, M. (2005) Testing for a unit root against smooth transition autogressive models, Working Paper No. 05-W10, Vanderbilt University, Nashville, Tennessee.

Pedroni, P. (1995) Panel cointegration: asymptotic and finite sample properties of pooled time series, with an application to the PPP hypothesis, Working Paper No. 95-013, Indiana University, Bloomington.

Pedroni, P. (1999) Critical values for cointegration tests in heterogeneous panels with multiple regressors, *Oxford Bulletin of Economics and Statistics*, **61**, 653–70.

Sarno, L. and Taylor, M. P. (2002) Purchasing power parity and the real exchange rate, *IMF Staff Papers*, **49**, 65–105.

Secu, P., Uppal, R. and Van Hall, C. (1995) The exchange in the presence of transaction costs: implications for tests of purchasing power parity, *Journal of Finance*, **50**, 1309–19.

Seo, M. (2003) Unit root test in a threshold autoregression: asymptotic theory and residual-based block bootstrap, *mimeo*, University of Wisconsin-Madison, Madison.

Taylor, M. P. (2006) Real exchange rates and purchasing power parity: mean-reversion in economic thought, *Applied Financial Economics*, **16**, 1–17.

Taylor, M. P., Peel, D. A. and Sarno, L. (2001) Nonlinear mean-reversion in real exchange rates: toward a solution to the purchasing power parity puzzles, *International Economic Review*, **42**, 1015–42.

Taylor, A. M. and Taylor, M. P. (2004) The purchasing power parity debate, *Journal of Economic Perspectives*, **18**, 135–58.

Teräsvirta, T. (1994) Specification, estimation and evaluation of smooth transition autoregressive models, *Journal of the American Statistical Association*, **89**, 208–18.

Tse, Y. K. and Ng, L. K. (1997) The cointegration of Asian currencies revisited, *Japan and the World Economy*, **9**, 109–14.

Wu, J. L., Tsai, L. J. and Chen, S. L. (2004) Are real exchange rates non-stationary? The Pacific basin perspective, *Journal of Asian Economics*, **15**, 425–38.