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8 February 2012

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Abstract

We utilize non-linear models to examine the stationarity of oil prices (Brent, Dubai, WIT and World) over the period 1973:2-2011:2. Real oil prices are calculated and expressed in the domestic currencies of seven Asian countries (Indonesia, Japan, Korea, Malaysia, the Philippines, Singapore and Thailand) and in the U.S dollar. Applying linear unit root tests with and without structural breaks shows very limited evidence of stationarity. However, applying non-linear models shows evidence of non-linearity in all the cases. In most cases, we find significant evidence of exponential smooth transition autoregression (ESTAR) type non-linearity. Notably, the results for Japan suggest logistic (LSTAR) type non-linearity for the four oil prices. Applying unit root tests, which account for two types of non-linearities (smooth transition and nonlinear deterministic trends), reveals evidence of stationarity in all the cases.

Keywords: oil prices; nonlinear unit root tests; nonlinear deterministic trends; smooth transition autoregression

JEL classification: O53; C22 ; Q43

1. Introduction

Oil prices have acquired increasing attention of both academicians and policy makers, especially after the oil shocks in the 1970s, and the recent sharp increases in oil prices between 2002 and 2008. Oil plays an important role in both oil-exporting and importing countries. In many oil-exporting countries, such as OPEC, national income heavily depends on crude oil exports. Thus, oil-price fluctuations can have a great impact on macroeconomic flows, such as incomes, savings, and current account balances. Recognizing that oil is the engine of economic activities, many studies have examined the impact of oil prices on different economic variables, such as exchanges rates, growth, investment, stock prices, inflation and unemployment. In particular, in the aftermath of the oil shocks in the 1970s, the U.S and other economies went into a recession. In view of that, many studies have attempted to understand the link between oil shocks and macroeconomic variables. Among others, Hamilton (1983) and Mork (1989) find a negative effect between oil price shocks and GDP and show that oil shocks are responsible for economic recessions. Zhou (1995) investigates different sources of real exchange rate shocks and finds that oil-price fluctuations play a major role in explaining real exchange rate movements. Chaudhuri and Daniel (1998) show that the nonstationary behavior of U.S dollar real exchange rate is due to the nonstationary behavior of real oil prices. Bergvall (2004) finds that real oil price shocks explain most of the long-run variance of the real exchange rate in

Norway and Denmark. Chen and Chen (2007) show that real oil prices may have been the dominant source of real exchange rate movements in the G7. Korhonen and Juurikkala (2009) find that an increase in the real oil price appreciates OPEC's real exchange rates.[1]

Du *et al*. (2010), using VAR analysis, find a significant effect of oil prices on growth and inflation in China. Jin (2008) finds a negative effect of oil price increase on growth in Japan and China. Rafiq *et al.* (2008) find that oil price volatility has a significant impact on unemployment and investment in Thailand. Cunado and Gracia (2005) find that oil price shocks Granger-cause economic growth in Japan, South Korea, and Thailand. Basher and Sadorsky (2006) examine the relationship between oil prices and stock prices for some emerging markets; and Park and Ratti (2008) for the U.S and 13 European countries, find that oil prices negatively affect stock prices.

Cuestas and Regis (2010) examine the order of integration of oil prices using non-linear unit root tests. They collect daily observations of the S&P crude oil price index for the period January, 1st, 1987 – June, 10th, 2008. Applying Bierens (1997) unit root test which assumes non-linear trend stationarity under the alternative hypothesis, Cuestas and Regis find that the oil price is stationary around a non-linear deterministic trend. Building on Cuestas and Regis' (2010) work, the objective of this paper is to use non-linear models to examine the time-series properties of oil prices for Indonesia, Japan, Korea, Malaysia, the Philippines, Singapore and Thailand. To achieve this, quarterly data is extracted from the IMF's International Financial Statistics online database over the period 1973:2-2011:2. The data contains the nominal exchange rate (defined as the market rate per U.S. dollar), the consumer price index (CPI), the British price of oil (Brent), the United Arab Emirates price (Dubai), West Taxes Intermediate price (WIT), and the World price of oil (World). The real oil prices in domestic currency are calculated by converting the U.S dollar price of oil into domestic currency and then deflated by the domestic CPI (2005 = 100).[2] All variables are measured in logarithms. We carry out a comprehensive treatment of the behavior of real oil prices by (1) testing formally for the presence of non-linearities in the real oil prices expressed in the domestic currencies of seven Asian countries (Indonesia, Japan, Korea, Malaysia, the Philippines, Singapore and Thailand) and in the U.S dollar; (2) differentiating between symmetrical and asymmetrical types of non-linearities; (3) examining the stationarity of the

[1] Other studies examining the link between oil prices and exchange rates include McGuirk, 1983; Krugman, 1983a, 1983b; Golub, 1983; Rogoff, 1991.

[2] Empirically, studies examining oil prices use either the U.S dollar oil price or this price converted into domestic currency using the market exchange rate. The main difference between the two variables is that fluctuations in oil prices expressed in domestic currency may be due to exchange rate fluctuations and/or fluctuations in the national price level.

real oil prices using unit root tests that allow for two types of non-linearities (smooth transition and nonlinear deterministic trends).

Previous studies examining the influence of oil prices on different economic variables (in particular, GDP) assume that the data-generating process (DGP) of oil prices is linear; therefore, they utilize oil price data in linear forms. Recently, however, there has been an increasing interest in examining non-linear adjustment in key economic variables, such as interest rates, inflation and real exchange rates, because if non-linearity is present but ignored and linear models, such as the Augmented-Dickey Fuller (ADF) unit root test, are used, this may result in a misleading conclusion about the time-series properties of the variables. For example, Pippenger and Goering (1993), Balke and Fomby (1997), Enders and Granger (1998), and Caner and Hansen (2001) show that linear unit root tests and cointegration tests have low power in the presence of nonlinearity. In particular, Pippenger and Goering argue that many economic relationships involve economic variables that have implicit transaction costs or arbitrage boundaries where arbitrage is too expensive and, thus, does not take place. They examine the power of unit root tests in detecting mean reversion in economic variables to long-run equilibrium in the presence of transaction costs and find that the power of these tests may fall dramatically under threshold processes.

Accordingly, oil prices may influence economic variables in a non-linear fashion. Indeed, the potential importance of considering non-linearities in oil prices can be found in the literature of oil prices and (mainly) GDP. Mork (1989) finds asymmetric effect of oil price increase and decrease on the U.S GDP. Akram (2004) points out to a non-linear asymmetric relationship between the nominal exchange rate of the krone and oil prices. Huang et al. (2005) find that oil price shocks have asymmetric effects on economic growth in Canada, Japan and the U.S. Cologni and Manera (2009), using different regime switching models for the G7 countries, find that different non-linear measures of oil prices contribute to better description of oil impact to output growth. Moreover, Hamilton (1996) proposes a non-linear modeling of oil data termed as "net oil price increase (NOPI)". Lee *et al.* (1995) propose another nonlinear measure of oil prices using Generalized Autoregressive Conditional Heteroskedasticity (GARCH) models known as "volatility adjusted series of oil price".

On the sectoral level, Keane and Prasad (1996), using tests to micro level panel data, provide evidence that higher oil prices negatively affect real wages, and that the effect varies between skilled and unskilled workers. Davis and Haltiwanger (2001), employing VAR in a sectoral format, show that oil shocks play a prominent role in the short-run fluctuations of job destruction and that oil prices response is asymmetric; only to job destruction and not to job creation. Francesco (2009) shows, with U.K. manufacturing and services sectors data, that in linear tests, oil price shocks have positive impact on both the output of manufacturing and services sectors while asymmetric specification reveals that oil price increases reduce manufacturing output but does not affect services sector. However, services sector responds to oil price decrease while manufacturing sector does not.

Different reasons have been offered to explain the sources of this non-linearity. For instance, Hamilton (1988) argues that the adjustment cost of oil price changes could be the reason for this asymmetry. Ferderer (1996) provides another explanation that sectoral shocks and uncertainty could be the reason. However, Bernanke *et al.* (1997) argue that the effect of an oil shock is not due to oil prices changes rather contractionary monetary policy is responsible for asymmetric effects of oil price shocks. Precisely, following an oil price increase, when oil prices pass through to core inflation, interest rates are raised by the monetary authority which consequently slows down economic growth. Moreover, it can be shown that the real oil price of a country (Japan) is simply the real exchange rate multiplied by the real oil price of the U.S. Accordingly, and given the link between oil prices and monetary policy through inflation and interest rates, it is already documented in the literature that interest rates, inflation and real exchange rates adjust non-linearly due to the presence of transaction costs, inflation targeting and structural breaks. Balke and Fomby (1997), for example, argue that adjustment to long-run equilibrium may exhibit a discontinuous behavior due to the presence of fixed adjustment costs, or transaction costs, or policy interventions, such as exchange rate management and commodity price stabilization. This may create a band in which prices may diverge and in which arbitrage opportunities exist. They characterize this behavior in terms of a threshold cointegration where the equilibrium error follows a threshold autoregression that is mean-reverting outside the band and has a unit root inside the band.

Other sources of non-linearity are inflation targeting and the opportunistic (approach to disinflation) behavior of central banks. According to Mishkin (2000), inflation targeting is a monetary-policy strategy that involves the public announcement of medium-term numerical targets for inflation and an institutional commitment to price stability as the primary goal of monetary policy. With the adoption of inflation targeting, the reaction of the central bank may vary depending on whether inflation is above or below a particular target. Given that the central bank can influence the short-term interest rate, if the central bank is more worried about high inflation, then it would increase the interest rate more aggressively when the expected rate of inflation is above its target level than when it is close or below the target (Christopoulos and Leon-Ledesma, 2007). With the increasing evidence of non-linear Phillips curve, Schaling (1999) extends inflation targeting with a non-linear Phillips curve and derives an asymmetric policy rule in which the nominal rate of interest responds more than one-for-one when forecast inflation is expected to increase and less than one-for-one when expected inflation is expected to decrease.

According to the proponents of the opportunistic approach to disinflation (Orphanides and Wilcox; 2002, and Aksoy *et al. ;* 2006), when inflation is moderate but still above the long-run target, the central bank should not take deliberate actions directed at fighting inflation but, rather, should wait for exogenous circumstances –such as favorable supply shocks and unforeseen recessions- to deliver the desired reduction in inflation. Similarly, when inflation is moderate but below the long-run objective, policymakers should not take deliberate countervailing actions but, rather, should wait for inflationary shocks and unforeseen expansions to bring inflation back toward the long-run level. On the other hand, when inflation is running substantially above or below its long-run target, policymakers should respond aggressively to bring inflation toward the long-run level.

Accordingly, inflation targeting and the opportunistic behavior of central banks can create a *"band of inaction"* around the target inflation level. If inflation is outside the band of inaction, policymakers will take deliberate actions to bring inflation toward the target level –inside the band. Precisely, policymakers should raise the interest rate when inflation is above the upper limit of the band and lower it when inflation is below the lower limit of the band. Once inside the band, policymakers should behave opportunistically by accommodating shocks that bring inflation towards the target level and should focus on stabilizing output and employment around their potential levels (Orphanides and Wilcox, 2002). Hence, the behavior of policymakers changes depending on whether inflation is inside or outside the band of inaction and, as a result, the time-series properties of inflation and interest rates change depending on whether inflation is inside or outside the band. Inside the band, they are divergent and may be characterized by unit root and outside the band they become mean reverting.

Prior to the 1997 Asian financial crisis, exchange rates in most of the crisis-hit countries were pegged to the U.S dollar under managed floating regimes, except the Philippines, which operated an independently floating regime. Reports from the IMF (1998) indicated that one of the major reasons for the crisis was the pegged exchange rates relative to the U.S dollar. Because of the crisis, most of the crisis-hit countries announced a shift from an exchange rate-based monetary policy framework to the explicit adoption of inflation targeting (Chow and Kim, 2006). Conventionally, an inflation-targeting regime is accompanied by a flexible exchange rate regime, with the interest rate used as the monetary policy instrument. In particular, Indonesia, Korea, the Philippines and Thailand announced the use of the interest rate as the key monetary policy-operating instrument (Chow and Kim, 2006). Since inflation targeting involves an institutional commitment to price stability as the primary goal of monetary policy, these countries have passed legal and institutional legislations to support their inflation targeting arrangements. Table 1 provides highlights of inflation targeting arrangements in these countries. Among the Asian crisis-hit countries, Malaysia is the exception, which shifted to a fixed exchange rate regime relative to the U.S dollar and imposed capital controls in September 1998 (Chow and Kim, 2006).

[INSERT TABLE 1 HERE]

Another source of nonlinearity may arise because of structural breaks. Bierens (1997) argues that the presence of breaks might imply a broken deterministic trend, which is a particular case of a nonlinear time trend. Therefore, even unit root tests that allow for structural breaks may lack power (Bierens 1997). Breaks are associated with significant economic and political events, such as changes in exchange rate regimes from fixed to managed or free float, financial crises, building up and bursting of bubbles, financial liberalization, and external forces, such as oil embargos and wars. The oil price shocks in the 1970s and the sharp increases in oil prices in recent years may have caused structural breaks in oil prices.

Besides the oil shocks of the 1970s that may have caused structural breaks in oil prices, in the 1980s and 90s some Asian countries experienced dramatic changes in their exchange rates due to the Plaza Accord in 1985 and the 1997 Asian crisis. Precisely, in September 1985 the finance ministers of the U.S, United Kingdom, France, West Germany, and Japan agreed that the U.S. dollar was overvalued against the yen. The countries agreed to depreciate the dollar and appreciate the yen by lowering the interest differential between the two countries (Miyagawa and Morita 2005). This resulted in a huge appreciation of the yen from an average of 240 yen per U.S dollar in 1985 to an average of 200 yen early 1986.

The Asian crisis, which started in Thailand early July 1997 with the collapse of the Thai baht due to severe speculative attacks, forced Thailand to adopt a managed floating exchange rate regime. The crisis quickly spread to neighboring countries and the currencies of Indonesia, Malaysia, the Philippines, Korea, and Singapore came under severe speculative attacks, which led to quick and huge depreciations in the countries' currencies with respect to the U.S. dollar and other major currencies.

Consequently, there are various reasons that make us believe that the behavior of oil prices may exhibit non-linearity. This will have implications for linear models. In particular, if the true process is non-linear, then linear models will have very low power to reject a false unit root null.

This paper proceeds as follows. The next section presents the methodology. Section three provides the empirical results and Section four gives summary and conclusion.

2. Methodology

Empirically, stationarity of economic variables has been examined by employing linear models such as the ADF unit root test, which is based on the assumption that the speed of adjustment occurs continually and at a constant rate, regardless of the size of deviations from the equilibrium level. Formally, the ADF test is implemented by estimating

$$\Delta P_{ot} = \alpha + \rho P_{ot-1} + \sum_{j=1}^{P} \lambda_j \Delta P_{ot-j} + \varepsilon_t \tag{1}$$

Where P_{ot} is the logarithm of real oil price. The null hypothesis of stationary P_{ot} $(H_0\colon \rho = 0)$ is tested against the stationary linear alternative $(H_A\colon \rho < 0)$. The speed of adjustment parameter (ρ) is assumed to occur continually and at a constant rate, regardless of the size of the deviation from equilibrium with a half-life deviation of $ln(0.5/1 + \rho)$.

Empirically, non-linearity is investigated through models that allow the autoregressive parameter (ρ) to vary. Such models include the smooth transition autoregression (STAR) model proposed by Granger and Terasvirta (1993). In this model, adjustment takes place in every period but the speed of adjustment varies with the extent of deviations from equilibrium. There are two variants of the STAR model: the exponential STAR (ESTAR) model and the logistic STAR (LSTAR) model. The ESTAR model implies that the behavior of the variable exhibits symmetrical adjustment for deviations above and below the equilibrium level, whereas the LSTAR model implies asymmetrical adjustment. It should be noted that selecting ESTAR or LSTAR, a priori, is inappropriate for modeling the behavior of economic variables; oil prices in our case. However, one might argue that given that non-linearity is present, it is important to identify whether the ESTAR or LSTAR better fits the data because different regimes may have different dynamics with the speed of convergence changing with the extent of deviation from equilibrium. Therefore, we consider the following representation of the STAR model for P_{ot}

$$\Delta P_{ot} = \alpha' + \rho' P_{ot-1} + \sum_{j=1}^{P} \lambda'_j \Delta P_{ot-j} + \left\{\alpha_0 + \rho_0 P_{ot-1} + \sum_{j=1}^{P} \lambda_{0j} \Delta P_{ot-j}\right\} F[\theta;\ P_{ot-d}] + \varepsilon_t \tag{2}$$

and then address the issue of whether the behavior of q_t follows symmetrical or asymmetrical adjustment. $F[\theta;\ P_{ot-d}]$ is the transition function bounded between zero and one, which determines the degree of mean-reversion. The transition function for the ESTAR model is given by $F[\theta;\ P_{ot-d}] = 1 - exp[-\theta(P_{ot-d} - \mu)^2]$, whereas for the LSTAR model is given by $F[\theta;\ P_{ot-d}] = \{1 + exp[-\theta(P_{ot-d} - \mu)]\}^{-1}$, where μ is the equilibrium level of P_{ot}, θ is a transition parameter, which determines the speed of transition between two extreme regimes with lower absolute values implying slower transition, d is a delay parameter suggesting that deviations from the equilibrium level generate increasingly mean reversion with a delay, and ε_t is a white noise with zero mean and constant variance.

In the absence of non-linearities ($\theta = 0$), the second term in (2) is zero and the model reverts to the linear ADF model defined in (1). However, if the true behavior of P_{ot} is governed by (2), then the linear ADF model would be misspecified and the estimate of ρ would be inconsistent as it would be estimating ρ as a combination of ρ' and ρ_0 in the true model (2). Thus, the crucial parameters are ρ' and ρ_0. As mentioned earlier, the speed of convergence to the equilibrium level would gradually increase as the deviation from equilibrium rises in absolute value. This implies that for small deviations, P_{ot} may be characterized by unit root or even explosive behavior; that is, $\rho' \geq 0$ is admissible, but for large deviations, P_{ot} is mean reverting; that is, we must have $\rho_0 < 0$ and $\rho' + \rho_0 < 0$ for global stability (Taylor *et al.* 2001).

Following Terasvirta (1994), the specification of the STAR model consists of three stages: first, specifying a linear autoregressive model; second, testing linearity for different values of the delay parameter (d), and if it is rejected, determining d and; third, choosing between ESTAR and LSTAR by testing a sequence of nested hypothesis. The purpose of the first stage is to determine the appropriate lag length (P), which can be chosen by inspecting the partial autocorrelation function or by using some information criterion, such AIC or SIC. In this paper AIC is used. The second stage involves testing for the presence of nonlinearities in the adjustment process of P_{ot} using the following specification

$$P_{ot} = \alpha_0 + \sum_{=1}^{P} \alpha_j P_{ot-j} + \sum_{j=1}^{P} \left(\beta_{1j} P_{ot-j} P_{ot-d} + \beta_{2j} P_{ot-j} P_{ot-d}^2 + \beta_{3j} P_{ot-j} P_{ot-d}^3\right) + \varepsilon_t \quad (3)$$

The null hypothesis of linearity (H_0: $\beta_{1j} = \beta_{2j} = \beta_{3j} = 0,\ for\ j = 1, \dots, P$) is tested against the alternative of non-linearity(H_A: $at\ least\ one\ \beta \neq 0$). Rejection of H_0 provides evidence in favor of the nonlinear STAR model. The null hypothesis may be tested by an ordinary *F-test*. In order to determine the delay parameter d, the linearity test in (3) is repeated for the range of values $1 \leq d \leq D$ (Terasvirta and Anderson 1992). If the linearity test is rejected for more than one value of d, the one that has the smallest *p-value* associated with the linearity test is selected. The third stage involves choosing between ESTAR and LSTAR-nonlinearity types. Following Terasvirta and Anderson (1992), this can be done by testing the following sequence of nested hypotheses:

$$H_{03}: \beta_{3j} = 0, for\ j = 1, \dots, P \tag{4}$$

$$H_{02}: \beta_{2j} = 0 \mid \beta_{3j} = 0, for\ j = 1, \dots, P \tag{5}$$

$$H_{01}: \beta_{1j} = 0 \mid \beta_{2j} = \beta_{3j} = 0, for\ j = 1, \dots, P \tag{6}$$

If H_{03} is rejected the LSTAR model is selected. If H_{03} is accepted and H_{02} is rejected, the ESTAR model is chosen. Accepting H_{03} and H_{02} and rejecting H_{01} implies selecting the LSTAR model. However, Granger and Terasvirta (1993) and Terasvirta (1994) argue that this sequence of testing may lead to selecting the wrong model if higher order terms of Taylor expansion used in deriving these tests are not considered. They propose basing the selection of the model on the lowest p-value associated with the *F-test* statistics for the sequence (4) – (6). In particular, after rejecting the general hypothesis of linearity (H_0), if the *p-value* of H_{03} or H_{01} is the smallest, then the LSTAR model is selected, and if H_{02} has the smallest *p-values*, ESTAR model is chosen.

2.1 Nonlinear Unit Root Tests

The mean reversion property of P_{ot} is examined using the nonlinear unit root tests developed by Kapetanios, Shin, and Snell (2003, hereafter, KSS) and Bierens (1997). In general, we can differentiate between two types of nonlinearities. First, the presence of trade barriers, foreign exchange interventions, or heterogeneous agents creates a band of no-arbitrage where arbitrage is simply too expensive and thus, does not take place. This implies that the oil price behaves as nonstationary when inside the band. However, once outside the band for a sufficiently long time, arbitrage takes place moving the oil price towards its long-run level and it becomes increasingly reverting with the size of the deviation from the equilibrium level. Michael *et al.* (1997), among others, argue that the shift between regimes is smooth rather than sudden because of time aggregation and individuals' behavior. To account for this possibility, the KSS test, which is based on smooth transition between regimes, is used. Moreover, the Asian countries may have experienced structural breaks over the sample period due to oil price shocks, Plaza Accord and the Asian crisis. Bierens argues that the presence of breaks might imply broken deterministic trends. A broken time trend is particular case of a nonlinear time trend. To account for this possibility, Bierens' test, which approximates the broken time trends by nonlinear deterministic trends, is used.

KSS test the unit root null against the alternative of nonlinear ESTAR but globally stationary process. The test is based on the following ESTAR model specification:

$$\Delta P_{ot} = \lambda P_{ot-1}[1 - \exp(-\theta P_{ot-1}^2)] + \varepsilon_t \tag{7}$$

Where P_{ot} is the de-meaned or de-trended oil price, θ is a parameter determining the speed of mean reversion, and ε_t is an i.i.d. error term with zero mean and constant variance. For variables containing nonzero mean and/or a linear deterministic trend, KSS use the de-meaned and/or de-meaned and de-trended data. The unit root null (H_0: $\theta = 0$) is tested against the alternative of nonlinear but globally stationary process (H_A: $\theta > 0$). However, testing this null directly is not feasible since λ is not identified under the null. To overcome this problem, KSS compute a first-order Taylor series approximation to the ESTAR model under the null to obtain the auxiliary regression

$$\Delta P_{ot} = \gamma P_{ot-1}^3 + \varepsilon_t \tag{8}$$

and to allow for serially correlated errors, the auxiliary regression in (8) is augmented to obtain the following specification

$$\Delta P_{ot} = \gamma P_{ot-1}^3 + \sum_{j=1}^{P} \beta_j \Delta P_{ot-j} + \varepsilon_t \tag{9}$$

Where P is the lag order. The null hypothesis of unit root to be tested in (8) or (9) is H_0: $\gamma = 0$, while the alternative is H_A: $\gamma < 0$.

Bierens (1997) argues that the presence of structural breaks might imply broken deterministic trends, which is a particular case of a nonlinear time trend. Bierens suggests approximating the broken time trends by nonlinear trends and proposes a test that considers the possibility of stationarity around a nonlinear deterministic trend under the alternative hypothesis. The test generalizes the ADF auxiliary regression by incorporating Chebishev polynomials in order to approximate the nonlinear deterministic trend. Bierens argues that because Chebishev polynomials are orthogonal and bounded, they have less power distortion than regular time polynomials. The ADF auxiliary regression with Chebishev polynomials is given by

$$\Delta P_{ot} = \gamma P_{ot-1} + \sum_{j=1}^{P} \beta_j \Delta P_{ot-j} + \theta^T \mathrm{N}_{t,n}^{(m)} + \varepsilon_t \tag{10}$$

Where $\mathrm{N}_{t,n}^{(m)} = (\mathrm{N}_{0,n}^*(t), \mathrm{N}_{1,n}^*(t), \ldots, \mathrm{N}_{m,n}^*(t))^T$ is a vector of Chebishev polynomials of order m, such that $\mathrm{N}_{0,n}^*(t) = 1$, $\mathrm{N}_{1,n}^*(t)$ is equivalent to a time trend, and $\mathrm{N}_{2,n}^*(t)$ to $\mathrm{N}_{m,n}^*(t)$ are cosine functions. The unit root null with a drift is tested against three alternative hypotheses: stationarity around a level, stationarity around a linear trend, or stationarity around a nonlinear trend. Under the null hypothesis, γ and the last m components of θ^T are zero. To test this hypothesis, Bierens proposes several tests. The $t(m)$ test, which is a t-test on the significance of the coefficient γ. The $A(m)$ test, which is an alternative test for the $t(m)$ test and thus, can be used to check the robustness of the results of the $t(m)$ test. The $F(m)$ test, which tests the joint hypothesis that the estimated coefficient γ and the last m components of θ^T are zero in specification (10) under the null hypothesis. Since the $t(m)$ and $A(m)$ tests are two-sided tests, when the null hypothesis is rejected, the proper alternative hypothesis and thus, the distinction between linear or nonlinear trend stationarity depends upon whether it is right-side or left-side rejection. Whereas right-side rejection (a p-value > 0.90) implies stationarity around a nonlinear deterministic trend, left-side rejections (a p-value < 0.10) are ambiguous as the tests can not differentiate between mean stationarity, linear trend stationarity, or nonlinear trend stationarity. However, with the $F(m)$ test, which is a one-side test (right-side rejection), rejections of the null hypothesis do not differentiate between the three alternatives.

When implementing Bierens' test, the order of the ADF auxiliary regression (P) and the order of Chebishev polynomials (m) need to be determined. Whereas the order P can be easily determined by some information criteria, such as SIC or AIC, determining the order of m is more difficult as Bierens argues that there is no unique way for choosing m. If m is chosen too low, it may be not sufficient to detect nonlinearity under the alternative hypothesis. If m is chosen too high, it may cause lack of power. Therefore, we report the results for different values of m. The order P is determined by AIC.

3. Results

A visual inspection of the real oil prices expressed in terms of domestic currencies, in figure 1, indicates that the prices are dominated by major and sometimes persistent shocks, especially around the oil price shocks in the 1970s, in the 80s coinciding with Iraq-Iran war and the collapse of oil prices in 1986, the Iraqi invasion of Kuwait in 1990/91 and the Gulf war, the 1997/98 Asian crisis, the 2001 terrorist attacks on the U.S, the Iraqi war in 2003, and the recent U.S mortgage crisis in 2008.

[INSERT FIGURE 1 HERE]

As a preliminary step, the stationarity of P_{ot} is examined using the ADF test. The number of lags is determined by AIC. The results in table 2 indicate that the unit root null could not be rejected at the conventional significance levels in any cases.

[INSERT TABLE 2 HERE]

However, the sample period under study is an historical period over which some Asian countries have experienced major economic and financial events that may have caused structural breaks in their oil prices. To explore this possibility, we apply Zivot and Andrews (1992) and Lumsdaine and Papell (1997) unit root tests. The Zivot-Andrews test allows for a single break endogenously determined and is based on three models. Model A allows for a one-time change in the mean of the series, model B allows for a one-time change in the slope of the trend function, and model C allows for a one-time change in both the mean and the slope of the trend function. The unit root null under each model is tested against the alternative of a deterministic trend with a change in either the mean, or the slope, or both. Lumsdaine and Papell (1997) extend Zivot-Andrews test to allow for two breaks and propose three models: Model AA, Model BB and Model CC. The tests are applied and the results[3], reported in table 3, suggest evidence of stationarity at the 5 percent significance level or lower in Indonesia for the four oil prices and with breaks in 1979:1 and 1997:2 coinciding with the second oil price shock and the Asian crisis, respectively. The results for Korea and the Philippines suggest stationarity for only Dubai oil price with breaks around 1979 and 1985.

[INSER TABLES 3 HERE]

The results reported in table 3 provide only limited support for the stationarity of oil prices. Thus, using models that allow for endogenously determined structural breaks in the data generating process of oil prices provides only very limited evidence of stationarity.

Although models that allow for structural breaks are more powerful than the linear ADF test in the presence of breaks, they do not consider non-linearities. If non-linearity is present, applying the aforementioned tests might be misleading. Because there are reasons that make us believe that non-linearities may be present in the behavior of oil prices, the next section explores this possibility using non-linear models.

3.1 Linearity Test

The results of conducting the linearity test are presented in table 4 over the range for the delay lag length $d \in \{1, \dots, 12\}$. In most cases, the optimum d order is between one and four quarters indicating a rather fast response to shocks and that market participants react to deviations with a delay of one to four quarters. The optimum autoregressive order (P) is determined by AIC. The table reports the *p-values* for test statistics $F - stat$ for the null hypothesis of linearity $(H_0: \beta_{1j} = \beta_{2j} = \beta_{3j} = 0)$ against the alternative of non-linearity (H_A at least one $\beta \neq 0$). If

[3] Since the results from the two tests are not significantly different and due to space limitation, only the results from Lumsdaine and Papell (1997) are reported. All unreported results are available upon request from the authors.

linearity is rejected for more than one value of d, the one that has the smallest *p-value* associated with the linearity test is selected. The results decisively reject the null of linearity at conventional significance levels in all cases, which suggests that the behavior of real oil prices expressed in the domestic currencies of these countries is non-linear over the range $d \in \{1, \dots, 12\}$.

[INSER TABLE 4 HERE]

Regarding the type of non-linearity, the results in table 5 decisively reject the null of linearity in favor of the ESTAR model in most cases. Notably, LSTAR-type non-linearity is established in Japan for the four oil prices. This suggests that in most cases, oil prices adjust symmetrically for price increase and decrease. In the case of Japan, the results suggest that oil prices adjust asymmetrically for oil price increase and decrease.

[INSER TABLE 5 HERE]

These findings of non-linearities have some important implications. First, linear models of unit root tests are misspecified and have very low power to reject a false unit root null. Second, given the significant amount of non-linearity present in oil prices, the results of previous studies employing linear models may not be valid. Third, we find strong evidence of symmetrical adjustment (ESTAR-type non-linearity) in most cases. This implies that the behavior of real oil prices when increasing to the equilibrium level is not different from its behavior when decreasing to the equilibrium level, except in the case of Japan.

3.2. Nonlinear Unit Root Tests

Table 6 presents the results of applying the KSS tests. Following KSS, we report three tests: the test on the raw data, the de-meaned data, and the de-meaned and de-trended series. The tests are applied with and without lags. The number of lags is selected by AIC.[4] The results suggest evidence of stationary oil prices in all the cases, except Japan where the null could not be rejected for the four oil prices, and Korea, the Philippines and the U.S, where null could not be rejected for Brent oil price.

[INSER TABLE 6 HERE]

The results from applying Bierens (1997) tests are reported in table 7. The p-values of the tests have been simulated with 5,000 replications by using a Gaussian $AR(P)$ process for ΔP_{ot} , where the order P of the ADF auxiliary regression is determined by AIC and the initial values have been taken from the actual series. The results are reported for different values of the Chebishev polynomials order(m). The results indicate that the unit root null

[4] The results with lags are not significantly different from those without lags.

can be rejected in all the cases. Precisely, in the majority of the cases the unit root null is rejected by the $t(m)$ and $A(m)$ tests, producing a left-side rejection, and the $F(m)$ with right-side rejection. With this outcome, it is not possible to distinguish between mean stationarity, linear trend stationarity, or stationarity around a nonlinear trend. In most cases, the unit root null is rejected for a low order of m ($m = 4\ or\ 5$). Although the unit root null is rejected for Japan by Bierens' tests (the $t(m)$ and $A(m)$ tests, producing a left-side rejection, and the $F(m)$ with right-side rejection) we cannot distinguish between the three alternatives. However, for $m = 2$, the unit root null is rejected in Japan for Dubai and World oil prices by the $t(m)$ test with a right-side rejection, indicating non-linear trend stationary. Also, the unit root null is rejected in Malaysia, Singapore and the U.S for WIT oil price by the $t(m)$ test with a right-side rejection, indicating non-linear trend stationary.

[INSER TABLE 7 HERE]

Thus, using the KSS and Bierens' tests that allow for non-linearities, we are able to find evidence of stationarity in all the cases. Our findings suggest that the behavior of real oil prices is non-linear; therefore, any analysis using oil prices should take into account these non-linearities. Our results are important from theoretical as well as policy-making perspectives. For instance, given the significant amount of non-linearities present in oil prices, applying linear models to oil prices may produce miss-leading results. Moreover, based on our results that real oil prices for the countries under consideration are non-linear stationary, shocks to oil prices will have only temporary effects, and they will tend revert to their long-run equilibrium levels. Hence, policy-makers in these countries may have some discretionary power over oil prices.

4. Summary and Conclusion

This paper utilizes non-linear models to examine the stationarity of real oil prices (Brent, Dubai, WIT and World) over the period 1973:2-2011:2. Real oil prices are calculated and expressed in the domestic currencies of seven Asian countries (Indonesia, Japan, Korea, Malaysia, the Philippines, Singapore and Thailand) and in the U.S dollar. We carry out a comprehensive treatment of the behavior of real oil prices by (1) testing formally for the presence of non-linearities in the real oil prices; (2) differentiating between symmetrical and asymmetrical types of non-linearities; (3) examining the stationarity of oil prices using unit root tests that allow for two types of non-linearities (smooth transition and nonlinear deterministic trends).

Applying linear unit root tests with and without structural breaks shows very limited evidence of stationarity. However, applying non-linear models shows evidence of non-linearity in all the cases. In most cases, we find significant evidence of exponential smooth transition autoregression (ESTAR) type non-linearity. Notably, the results for Japan suggest logistic (LSTAR) type non-linearity for the four oil prices. Applying unit root tests that account for two types of non-linearities (smooth transition and nonlinear deterministic trends) reveals evidence of stationarity in all the cases.

The results suggest that linear models may not be appropriate in modeling the behavior of oil prices. Also, imposing, a priori, the type of non-linearity may not be appropriate for modeling the behavior of oil prices. However, one might argue that given that non-linearity is present, it is important to identify whether the ESTAR or LSTAR better fits the data because different regimes may have different dynamics with the speed of convergence changing with the extent of deviation from equilibrium. A possible explanation for these non-linearities is the existence of trade barriers, such as transport and transaction cost, which can create a band within which prices are non-stationary. Another explanation is the existence of structural breaks. Our results are important from theoretical and policy-making perspectives. For instance, given the significant amount of non-linearities present in oil prices for the countries under consideration, applying linear models to oil prices may produce miss-leading results. Moreover, based on our results that real oil prices are non-linear stationary, shocks to oil prices will have only temporary effects, implying that oil prices are mean-reverting. Hence, policy-makers in these countries may have some discretionary power over oil prices.

References

Akram, Q.F. (2004). Oil prices and exchange rates: Norwegian experience. Econometrics Journal. 7, 476-504.

Aksoy, Y., Orphanides, A., Small, D., Wieland, V., Wilcox, D. (2006). A quantitative exploration of the opportunistic approach to disinflation. Journal of Monetary Economics. 53, 1877-1893.

Balke, N., Fomby, T. (1997). Threshold cointegration. International Economic Review 38(3), 627-645.

Bergvall, A. (2004). What determines real exchange rates? The Nordic countries. Scandinavian Journal of Economics. 106, 315-337.

Basher, S., Sadorsky, P. (2006). Oil price risk and emerging stock markets. Global Finance Journal. 17 (2), 224-251.

Bernanke, B., Gertler, M., Watson, M. (1997). Systematic monetary policy and the effects of oil price shocks. Brookings Papers on Economic Activity. (1), 91-142.

Caner M, Hansen B (2001). Threshold autoregression with a unit root. Econometrica 69(6), 1555-1596.

Cavoli, T., Rajan, R. (2006). Inflation targeting arrangements in Asia: exploring the role of the exchange rate. Singapore Center for Applied and Policy Economics, SCAPE Working Paper Series, Paper No. 2006/03 – Jan 2006.

Chaudhuri, K., Daniel, C. (1998). Long-run equilibrium real exchange rates and oil prices. Economics Letters. 58(2), 231–238.

Chen, S.S., Chen, H.C., (2007). Oil prices and real exchange rates. Energy Economics. 29, 390–404.

Christopoulos, D., Leon-Ledesma, M. (2007). A long-run non-linear approach to the Fisher effect. Journal of Money, Credit and Banking. 39(2-3), 543-559.

Chow, H., Kim, Y. (2006). Does greater exchange rate flexibility affect interest rates in post-crisis Asia? Journal of Asian Economics. 17, 478-493.

Cologni, A., Manera, M. (2009). The asymmetric effects of oil shocks on output growth: A Markov-switching analysis for the G-7 countries. Economic Modelling. 26(1), 1-29.

Cuesta, J., Regis, P. (2010). Nonlinearities and the order of integration of oil prices. The Empirical Economics Letters. 9(2), 193-202.

Cunado, J., Gracia, F. (2005). Oil prices, economic activity and inflation: Evidence for some Asian countries. Quarterly Review of Economics and Finance. 45(1), 65-83.

Davis, S., Haltiwanger, J. (2001). Sectoral job creation and destruction responses to oil price changes. Journal of Monetary Economics. 48 (3), 465-512.

Enders, W., Granger, C. (1998). Unit-root tests and asymmetric adjustment with an example using the term structure of the interest rates. Journal of Business and Economic Statistics 16(3), 304-311.

Ferderer, J. (1996). Oil price volatility and the macroeconomy: A solution of the asymmetry puzzle. Journal of macroeconomics. 18(1), 1-26.

Golub, S. (1983). Oil Prices and Exchange Rates. Economic Journal. 93, 576-93.

Granger, C., Terasvirta, T. (1993). Modeling nonlinear economic relationships. Oxford University Press, Oxford.

Hamilton, J. (1983). Oil and the macroeconomy since World War II. The Journal of Political Economy. 91(2), 228–248.

Hamilton, J. (1988). A neoclassical model of unemployment and business cycles. Journal of Political Economy. 96, 593-617.

Hamilton, J. (1996). This is what happened to the oil price-macroeconomy relationship. Journal of Monetary Economics. 38(2): 215-220.

Hamilton, J. (2011). Historical Oil Shocks- NBER Working Paper No. 16790**.**

Huang, B., Hwang, M., Peng, H. (2005). The Asymmetry of the Impact of Oil Price Shocks on Economic Activities: An Application of the Multivariate Threshold Model. Energy Economics. 27(3), 455-476.

Jin, G. (2008). The impact of oil price shock and exchange rate volatility on economic growth: A comparative analysis for Russia, Japan and China. Research Journal of International Studies. 8(11), 98-111.

Kapetanios, G., Shin, Y., Snell, A. (2003). Testing for a unit root in the nonlinear STAR framework. Journal of Econometrics. 112, 359-379.

Keane, M., Prasad, E.S. (1996). The employment and wage effects of oil price changes: A sectoral analysis. Review of Economics and Statistics. 78 (3): 389-400.

Korhonen, I., Juurikkala, T., 2009. Equilibrium exchange rates in oil-exporting countries. Journal of Economics and Finance. 33(1), 71−79.

Krugman, P. (1983a). Oil and the dollar in Economic Interdependence and Flexible Exchange Rates. Cambridge: MIT Press.

Krugman, P. (1983b). Oil shocks and exchange rate dynamics in Exchange Rates and International Macroeconomics. University of Chicago Press.

Lee, K., Ni, S., Ratti, R. (1995). Oil shocks and the macroeconomy: The role of price variability. Energy Journal. 16(4): 39-56.

Lumsdaine, R., Papell, D. (1997). Multiple trend breaks and the unit root hypothesis. Review of Economics and Statistics. 79, 212-218.

Michael, P., Nobay, A., Peel, D. (1997). Transaction costs and nonlinear adjustment in real exchange rates: an empirical investigation. Journal of Political Economy. 105: 862-879.

McGuirk, A. (1983). Oil price changes and real exchange rate movements among industrial countries. International Monetary Fund Staff Papers. 30, 843-83.

Mishkin, F. (2000). Inflation targeting in emerging-market countries. The American Economic Review. 90(2), 105-109.

Miyagawa, S., Morita, Y. (2005). Lessons from Japan's prolonged recession. Tampere Economic Working papers, Net Series, Working Paper 44, University of Tampere, Finland, htt://tampub.uta.fi/econet/wp44-2005.pdf.

Mork, K. (1989). Oil and the macroeconomy when prices go up and down: an extension of Hamilton's results. The Journal of Political Economy. 97(3), 740–744.

Orphanides, A., Wilcox, D. (2002). The opportunistic approach to disinflation. International Finance. 5(1), 47-71.

Park, J., Ratti, R. (2008). Oil price shocks and stock markets in the U.S. And 13 European countries. Energy Economics. 30(5): 2587-2608.

Pippenger, M., Goering, G. (1993). A note on the empirical power of unit root tests under threshold processes. Oxford Bulletin of Economics and Statistics 55(4):473-481.

Rafiq, S., Salim, R., Bloch, H. (2008). Impact of crude oil price volatility on economic activities: An empirical investigation in the Thai economy. Resources Policy. 34(3), 121–132.

Rogoff, K. (1991). Oil, productivity, government spending and the real yen dollar exchange rate. Working Paper, Federal Reserve Bank of San Francisco, San Francisco, CA.

Schaling, E. (1999). The non-linear Phillips curve and inflation forecast targeting. Bank of England Working Paper.

Taylor, M., Peel, D. A., Sarno L. (2001). Nonlinear mean-reversion in real exchange rates: toward a solution to the purchasing power parity puzzles. International Economic Review. 42(4):1015-1042.

Terasvirta, T. (1994). Specification, estimation and evaluation of smooth transition autoregressive models. Journal of the American Statistical Association. 89, 208-218.

Terasvirta, T., Anderson, H. (1992). Characterizing nonlinearities in business cycles using smooth transition autoregressive model. Journal of Applied Econometrics. 7, S119-S136.

Zhou, S. (1995). The response of real exchange rates to various economic shocks. Southern Economic Journal. 61(4), 936–954.

Zivot, E., Andrews, D. (1992). Further evidence on the great crash, the oil-price shock, and the unit root hypothesis. Journal of Business and Economic Statistics. 10(3), 251-270.

Table 1: highlights of inflation targeting arrangements in some Asian countries (as of July 2005)

Country	Date of initiation of inflation targeting	Target price index	Target rate	Target horizon
Indonesia	May 1999	Headline CPI	5 - 6%	3 years
Korea	January 1998	Core CPI (excluding non-cereal agricultural product and petroleum products	2.5 – 3.5%	1 year indefinite
Philippines	December 2001	Headline CPI. Also monitors core CPI (excluding agricultural product and petroleum products)	4 – 6%	2 years
Thailand	April 2000	Core CPI (excluding fresh food and energy)	0 – 3.5%	indefinite

Source: Cavoli and Rajan (2006).

Table 2: ADF unit root test of real oil prices

Variable	Test	Indonesia	Japan	Korea	Malaysia	Philippines	Singapore	Thailand	U.S
P_{Brent}	Trend	-3.62(1)**	-1.27(4)	-0.79(5)	-1.10(5)	-1.28(6)	-1.03(5)	-1.11(5)	-0.78(5)
	No trend	-2.32(2)	-1.45(4)	-0.84(5)	-0.71(5)	-1.21(6)	-1.06(5)	-0.91(5)	-0.94(5)
P_{Dubai}	Trend	-3.49(2)**	-1.31(4)	-2.02(2)	-1.09(5)	-2.29(2)	-1.02(5)	-1.10(5)	-0.77(5)
	No trend	-2.62(2)	-1.45(4)	-2.02(2)	-0.70(5)	-2.32(2)	-1.03(5)	-0.88(5)	-0.88(5)
P_{WIT}	Trend	-3.80(1)*	-1.34(6)	-1.01(5)	-1.35(5)	-1.46(6)	-1.25(5)	-1.27(5)	-0.99(5)
	No trend	-1.54(4)	-1.50(6)	-0.97(5)	-1.00(5)	-1.35(6)	-1.25(5)	-1.08(5)	-1.05(5)
P_{World}	Trend	-3.86(1)*	-1.39(4)	-0.93(5)	-1.44(6)	-1.40(6)	-1.12(5)	-1.22(5)	-0.90(5)
	No trend	-2.62(2)	-1.52(4)	-0.90(5)	-1.04(6)	-1.28(6)	-1.11(5)	-0.98(5)	-0.99(5)

*, **, denotes rejection of the null hypothesis of a unit root at the 1 and 5 percent significance levels, respectively. The 1 and 5 percent critical values are -4.02 and -3.44 for the trend model and -3.47 and -2.88 for the no-trend model. P_{Brent}, P_{Dubai}, P_{WIT}, and P_{World} stand for the real oil price of Brent, Dubai, West Taxes Intermediate and World, respectively. Number of lags is selected by AIC.

Table 3: Lumsdaine-Papell unit root test for real exchange rates and real oil prices (two breaks)

Variable	Test	Indonesia	Japan	Korea	Malaysia	Philippines	Singapore	Thailand	U.S
P_{Brent}	Model AA	-5.72(2)	-5.11(4)	-4.83(5)	-4.04(5)	-4.53(6)	-4.16(5)	-4.46(5)	-4.17(5)
	TB1	1985:04	1985:04	1985:04	1985:04	1984:02	1985:04	1985:04	1985:04
	TB2	1990:04	2003:04	1990:04	2003:02	1990:04	1990:04	1990:04	2003:04
	Model BB	-5.33(2)	-4.50(4)	-5.07(5)	-4.54(5)	-4.68(6)	-4.84(5)	-4.77(5)	-4.33(5)
	TB1	1981:01	1981:01	1981:01	1980:01	1980:01	1980:01	1980:01	1985:01
	TB2	1994:04	1994:04	1995:01	1995:02	1995:04	1995:04	1995:01	1997:03
	Model CC	-7.04(2)**	-5.31(4)	-5.22(5)	-4.12(5)	-4.98(6)	-4.24(5)	-4.55(5)	-4.27(5)
	TB1	1979:01	1985:04	1985:04	1982:02	1984:02	1981:03	1985:04	1985:04
	TB2	1997:02	1992:04	1999:01	1999:01	1999:02	1999:01	1999:01	1997:04
P_{Dubai}	Model AA	-6.33(2)**	-5.40(4)	-6.74(2)**	-4.32(5)	-6.17(2)**	-4.38(5)	-4.79(5)	-4.34(5)
	TB1	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04
	TB2	1990:04	2004:04	2004:04	1990:04	1990:04	1990:04	1990:04	2004:04
	Model BB	-5.70(2)	-4.59(4)	-6.26(2)	-4.69(5)	-5.74(2)	-4.99(5)	-4.95(5)	-4.23(5)
	TB1	1981:01	1981:01	1981:04	1980:01	1981:01	1980:01	1980:01	1980:01
	TB2	1994:02	1994:02	1994:02	1994:04	1995:03	1995:02	1994:02	1995:04
	Model CC	-7.92(2)*	-5.44(4)	-8.04(2)*	-4.09(5)	-7.34(2)*	-4.23(5)	-4.70(5)	-4.32(5)
	TB1	1979:01	1985:04	1979:01	1982:02	1979:01	1981:03	1985:04	1985:o4
	TB2	1997:02	1992:04	1993:02	1993:02	1999:01	1993:02	1999:01	1997:04
P_{WIT}	Model AA	-5.95(1)	-5.08(6)	-5.21(5)	-4.31(5)	-4.62(6)	-4.43(5)	-4.71(5)	-4.58(5)
	TB1	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04	1985:4
	TB2	1990:04	2003:04	1990:04	1990:04	1990:04	1990:04	1990:04	2003:04
	Model BB	-5.63(1)	-4.48(6)	-5.09(5)	-4.40(5)	-4.52(6)	-4.66(5)	-4.51(5)	-4.28(5)
	TB1	1980:04	1981:02	1981:02	1980:01	1980:02	1980:02	1980:02	1980:01
	TB2	1994:02	1994:02	1994:04	1995:01	1995:04	1995:03	1994:04	1997:03
	Model CC	-7.31(1)*	-5.23(6)	-5.45(5)	-4.08(5)	-4.79(6)	-4.09(5)	-4.45(5)	-4.30(5)
	TB1	1979:01	1985:04	1985:04	1985:04	1984:02	1979:04	1985:04	1985:04
	TB2	1997:02	1992:04	1993:02	1991:04	1999:02	1993:02	1999:01	1997:04
P_{World}	Model AA	-6.11(1)	-5.21(4)	-5.11(5)	-4.51(6)	-4.70(6)	-4.37(5)	-4.72(5)	-4.30(5)
	TB1	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04	1985:04	1985:4
	TB2	1990:04	2003:03	1990:04	1990:04	1990:04	1990:04	1990:04	2003:04
	Model BB	-5.69(1)	-4.55(4)	-5.01(5)	-4.83(6)	-4.71(6)	-4.82(5)	-4.74(5)	-4.36(5)
	TB1	1981:01	1981:01	1981:01	1980:01	1981:01	1980:01	1980:01	1980:01
	TB2	1994:02	1994:02	1994:04	1995:03	1995:04	1995:03	1995:01	1997:03
	Model CC	-7.62(1)*	-5.42(4)	-5.25(5)	-4.43(6)	-5.01(6)	-4.18(5)	-4.66(5)	-4.40(5)
	TB1	1978:04	1985:04	1985:04	1982:04	1984:02	1981:03	1985:04	1985:04
	TB2	1997:02	1992:04	1999:01	1999:01	1999:01	1993:02	1999:01	1997:04

*, ** denotes rejection of the null hypothesis of a unit root at the 1% and 5% significance level. The 1% and 5% are -6.74 and -6.16 for Model AA, -7.19 and -6.62 for Model BB, -7.19 and -6.75 for Model CC. The test allows for two breaks in the intercept, the trend or both at unknown locations. P_{Brent}, P_{Dubai}, P_{WIT}, and P_{World} stand for the real oil price of Brent, Dubai, West Taxes Intermediate and World, respectively. Number of lags is selected by AIC.

Table 4: Linearity test

Variable	Test	Indonesia	Japan	Korea	Malaysia	Philippines	Singapore	Thailand	U.S
P_{Brent}	P	1	5	1	3	3	3	6	3
	d	1	3	1	2	3	4	3	4
	$F-Stat$	3.138	2.2488	3.0535	9.4714	1.9799	2.6971	1.6352	3.4162
		[0.0273	[0.0078]	[0.0304]	[0.0000]	[0.0461]	[0.0064]	[0.0614]	[0.0008]
P_{Dubai}	P	1	2	1	3	3	3	3	3
	d	1	2	1	2	3	3	2	3
	$F-Stat$	4.4567	2.5979	5.5199	12.2774	7.9752	10.1507	11.1247	8.3007
		[0.0050]	[0.0203]	[0.0013]	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
P_{WIT}	P	2	1	1	4	3	2	6	6
	d	1	2	2	2	3	3	3	3
	$F-Stat$	3.0601	5.6311	4.9626	3.8889	3.9588	5.8969	2.1387	2.1798
		[0.0076]	[0.0011]	[0.0026]	[0.0000]	[0.0002]	[0.0000]	[0.0080]	[0.0067]
P_{World}	P	1	1	1	3	3	3	3	2
	d	1	2	1	2	3	3	2	3
	$F-Stat$	3.6949	3.0105	4.5285	12.4666	6.9402	9.1993	10.3229	8.4201
		[0.0133]	[0.0322]	[0.0046]	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]

The appropriate lag length (P) in the AR model is determined by AIC. The optimal d is selected by minimizing the p-value associated with the linearity test in (5) over the range $\{1, \dots, 12\}$.The $F-Stat$ tests the null hypothesis of linearity against the alternative of nonlinearity. The numbers in square brackets are the p-values associated with the linearity test.

Table 5: Specification of the type of the nonlinear model (ESTAR or LSTAR)

Variable	Test	Indonesia	Japan	Korea	Malaysia	Philippines	Singapore	Thailand	U.S
P_{Brent}	H_{03}	2.0783	0.9701	0.2373	5.6592	0.8436	2.2933	0.4264	4.0518
		[0.1515]	[0.4385]	[0.6268]	[0.0011]	[0.4722]	[0.0806]	[0.8603]	[0.0085]
	H_{02}	7.2439	1.7025	4.1779	15.6461	3.2269	2.7857	3.4579	2.6383
		[0.0079	[0.1384]	[0.0427]	[0.0000]	[0.0245]	[0.0431]	[0.0034]	[0.0520]
	H_{01}	0.0647	3.7663	4.6318	3.9255	1.7628	2.7325	0.9782	3.1077
		[0.7996]	[0.0033]	[0.0330]	[0.0100]	[0.1572]	[0.0462]	[0.4430]	[0.0286]
	Model	ESTAR	LSTAR	LSTAR	ESTAR	ESTAR	ESTAR	ESTAR	LSTAR
P_{Dubai}	H_{03}	4.9921	1.7681	2.4736	10.7253	3.2162	3.8520	5.5342	5.6369
		[0.0270]	[0.1743]	[0.1179]	[0.0000]	[0.0248]	[0.0109]	[0.0013]	[0.0011]
	H_{02}	8.2209	2.7848	13.9296	19.3341	11.3329	14.1688	16.9726	11.3101
		[0.0047]	[0.0651]	[0.0003]	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
	H_{01}	0.0057	3.0656	0.0487	1.9509	6.7882	8.3579	6.2645	5.1285
		[0.9398]	[0.0497]	[0.8257]	[0.1243]	[0.0003]	[0.0000]	[0.0000]	[0.0022]
	Model	ESTAR	LSTAR	ESTAR	ESTAR	ESTAR	ESTAR	ESTAR	ESTAR
P_{WIT}	H_{03}	0.6742	9.6724	0.6381	2.3448	0.6289	0.2362	0.4649	1.2618
		[0.5111]	[0.0022]	[0.4257]	[0.0576]	[0.5975]	[0.7899]	[0.8332]	[0.2792]
	H_{02}	3.5613	0.2639	0.5820	4.2621	6.6439	15.6518	4.8085	3.4236
		[0.0309]	[0.6082]	[0.4467]	[0.0028]	[0.0003]	[0.0000]	[0.0002]	[0.0036]
	H_{01}	4.7021	6.6265	13.5655	4.1989	4.0490	1.6171	1.0506	1.5848
		[0.0105]	[0.0110]	[0.0003]	[0.0031]	[0.0086]	[0.2021]	[0.3962]	[0.1571]
	Model	LSTAR	LSTAR	LSTAR	ESTAR	ESTAR	ESTAR	ESTAR	ESTAR
P_{World}	H_{03}	3.0906	3.8162	1.6606	10.2212	2.3043	3.0416	5.0622	2.2674
		[0.0808]	[0.0526]	[0.1995]	[0.0000]	[0.0794]	[0.0310]	[0.0023]	[0.1072]
	H_{02}	7.6717	0.4080	11.6580	19.8490	9.8472	13.8747	15.6418	19.6702
		[0.0063]	[0.5240]	[0.0008]	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
	H_{01}	0.2398	4.7161	0.2191	2.3217	6.7037	7.4199	6.2199	2.3223
		[0.6250]	[0.0315]	[0.6405]	[0.0779]	[0.0003]	[0.0001]	[0.0005]	[0.1018]
	Model	ESTAR	LSTAR	ESTAR	ESTAR	ESTAR	ESTAR	ESTAR	ESTAR

The first number is the *F-test* for the corresponding hypothesis and the second number in the square bracket is the *p-value* associated with the test. After rejecting the general hypothesis of linearity (H_0), if the *p-value* of H_{03} or H_{01} is the smallest, then the LSTAR model is selected, and if H_{02} has the smallest *p-values*, ESTAR model is chosen.

Table 6: The KSS unit root test

Variable	Test	Indonesia	Japan	Korea	Malaysia	Philippines	Singapore	Thailand	U.S
No lags									
P_{Brent}	t_{NL}^{R}	-2.16	-1.78	-2.10	-3.48*	-2.18	-2.37**	-2.02	-2.20
	t_{NL}^{D}	-3.24**	-2.01	-2.80	-3.65*	-3.14**	-3.00**	-3.40**	-2.44
	t_{NL}^{T}	-3.02	-2.31	-2.77	-3.14	-2.71	-2.82	-2.85	-2.54
P_{Dubai}	t_{NL}^{R}	-2.30**	-1.90	-2.29**	-4.79*	-2.26**	-3.59*	-2.07	-3.28*
	t_{NL}^{D}	-4.11*	-2.35	-3.74*	-4.54*	-4.53*	-4.42*	-4.61*	-3.78*
	t_{NL}^{T}	-3.97*	-2.78	-3.58**	-4.25*	-3.88**	-4.00*	-3.95*	-3.74*
P_{WIT}	t_{NL}^{R}	-2.27**	-1.82	-2.24**	-3.60*	-2.33**	-2.52**	-2.18	-2.44**
	t_{NL}^{D}	-3.07**	-2.30	-3.35**	-3.77*	-3.60*	3.57*	-3.73*	-3.09**
	t_{NL}^{T}	-3.09	-2.66	-3.21	-3.38	-3.01	-3.12	-3.13	-3.01
P_{World}	t_{NL}^{R}	-2.29**	-1.93	-2.32**	-4.47*	-2.31**	-3.39*	-2.13	-3.08*
	t_{NL}^{D}	-3.87*	-2.29	-3.66*	-4.44*	-4.33*	-4.29*	-4.47*	-3.62*
	t_{NL}^{T}	-3.87**	-2.66	-3.49*	-4.12*	-3.60**	-3.81**	-3.76**	-3.53**
Lags									
P_{Brent}	t_{NL}^{R}	-2.17(2)	-1.53(4)	-1.68(2)	-3.67(2)*	-1.87(2)	-2.37(2)**	-1.81(2)	-2.13(2)
	t_{NL}^{D}	-3.63(2)*	-2.36(4)	-2.35(2)	-3.95(2)*	-2.88(2)	-2.97(2)**	-3.34(2)**	-2.33(2)
	t_{NL}^{T}	-2.94(2)	-2.78(4)	-2.32(2)	-3.00(2)	-2.38(2)	-2.75(2)	-2.61(2)	-2.44(2)
P_{Dubai}	t_{NL}^{R}	-2.33(2)**	-1.53(4)	-1.87(2)	-6.90(2)*	-1.92(2)	-4.14(2)*	-1.82(2)	-3.42(2)*
	t_{NL}^{D}	-5.39(2)*	-2.55(4)	-3.50(2)*	-6.02(2)*	-5.00(2)*	-5.17(2)*	-5.43(2)*	-3.94(2)*
	t_{NL}^{T}	-4.14(2)*	-2.88(4)	-3.23(2)	-4.62(2)*	-3.80(2)**	-4.38(2)*	-3.97(2)*	-3.87(2)**
P_{WIT}	t_{NL}^{R}	-2.30(2)**	-1.63(6)	-1.96(2)	-4.02(2)*	-2.15(2)	-2.74(2)**	-2.09(2)	-2.53(2)**
	t_{NL}^{D}	-3.65(2)*	-2.55(6)	-3.07(2)**	-4.47(2)*	-3.73(2)*	-3.94(2)*	-4.12(2)*	-2.44(4)
	t_{NL}^{T}	-3.11(2)	-2.95(4)	-2.91(2)	-2.27(6)	-2.89(2)	-3.26(2)	-3.10(2)	-2.39(4)
P_{World}	t_{NL}^{R}	-2.38(2)**	-1.63(4)	-1.97(2)	-5.93(2)*	-2.07(2)	-3.94(2)*	-1.96(2)	-3.27(2)*
	t_{NL}^{D}	-4.97(2)*	-2.60(4)	-3.46(2)**	-5.84(2)*	-4.75(2)*	-5.02(2)*	-2.11(5)	-2.20(3)
	t_{NL}^{T}	-4.09(2)*	-2.91(4)	-3.19(2)	-4.47(2)*	-3.52(2)**	-4.14(2)*	-2.44(3)	-2.20(3)

t_{NL}^{R}, t_{NL}^{D}, t_{NL}^{T}denotes that the test is applied on the raw, de-meaned, and de-meaned and de-trended oil prices, respectively. *, **, *** denote rejection of the null hypothesis of unit root at the 1%, 5%, and 10% significance levels, respectively. The 1%, 5%, and 10% critical values are -2.82, -2.22, and -1.92 for the raw data, -3.48, -2.93, and -2.66 for de-meaned data, -3.93, -3.40, and -3.13 for de-trended data. Source: Kapetanios et al. (2003). Number of lags is selected by AIC.

Table 7: Bierens' (1997) nonlinear unit root tests

$m = 2$		P_{Brent}				P_{Dubai}				P_{WIT}				P_{World}		
Country	P	$t(m)$	$A(m)$	$F(m)$	P	$t(m)$	$A(m)$	$F(m)$	P	$t(m)$	$A(m)$	$F(m)$	P	$t(m)$	$A(m)$	$F(m)$
Indonesia	0	0.181	0.101	0.755	0	0.143	**0.083**	0.822	0	0.192	0.121	0.774	0	0.124	**0.068**	0.850
Japan	1	0.825	0.697	0.117	0	**0.903**	0.850	0.110	1	0.825	0.705	0.148	0	**0.901**	0.840	0.113
Korea	0	0.774	0.608	0.140	0	0.706	0.501	0.262	0	0.792	0.639	0.201	0	0.691	0.488	0.278
Malaysia	0	0.722	0.552	0.256	0	0.603	0.413	0.449	5	**0.990**	**0.988**	0.031	0	0.589	0.412	0.459
Philippines	0	0.717	0.541	0.204	0	0.627	0.431	0.351	0	0.770	0.630	0.255	0	0.619	0.438	0.353
Singapore	0	0.845	0.734	0.142	0	0.759	0.599	0.302	5	**0.995**	**0.995**	0.056	0	0.764	0.606	0.293
Thailand	0	0.695	0.527	0.231	0	0.610	0.431	0.388	0	0.744	0.603	0.304	0	0.599	0.414	0.399
U.S	0	0.840	0.704	0.095	0	0.769	0.589	0.212	5	**0.984**	**0.983**	0.009	0	0.758	0.573	0.216
$m = 4$																
Indonesia	0	0.141	0.135	0.744	0	**0.091**	0.110	0.835	0	0.266	0.253	0.596	0	0.127	0.131	0.767
Japan	1	**0.036**	**0.040**	**0.948**	0	0.154	0.231	0.888	1	**0.077**	**0.097**	**0.909**	0	0.203	0.280	0.856
Korea	0	**0.011**	**0.024**	**0.986**	0	**0.009**	**0.024**	**0.990**	0	**0.039**	**0.074**	**0.968**	0	**0.011**	**0.030**	**0.988**
Malaysia	0	**0.064**	0.105	**0.936**	0	**0.031**	**0.062**	**0.973**	5	0.894	0.865	0.203	0	**0.041**	**0.083**	**0.963**
Philippines	0	**0.067**	**0.082**	**0.911**	0	**0.027**	**0.050**	**0.969**	0	0.197	0.229	0.837	0	**0.052**	**0.077**	**0.936**
Singapore	0	0.120	0.160	**0.915**	0	**0.058**	0.102	**0.965**	5	**0.905**	0.871	0.296	0	**0.089**	0.133	**0.945**
Thailand	0	**0.056**	**0.081**	**0.929**	0	**0.028**	**0.059**	**0.971**	0	0.164	0.224	0.869	0	**0.042**	**0.077**	**0.953**
U.S	0	**0.049**	**0.086**	**0.996**	0	**0.016**	**0.043**	**0.987**	5	0.659	0.540	0.450	0	**0.032**	**0.070**	**0.975**
$m = 5$																
Indonesia	0	**0.068**	**0.091**	0.779	0	**0.033**	**0.057**	0.897	0	0.110	0.154	0.728	0	**0.050**	**0.080**	0.832
Japan	1	**0.028**	**0.051**	**0.908**	0	0.180	0.272	0.823	1	**0.056**	**0.098**	0.880	0	0.242	0.352	0.749
Korea	0	**0.007**	**0.021**	**0.983**	0	**0.002**	**0.008**	**0.994**	0	**0.012**	**0.035**	**0.975**	0	**0.004**	**0.019**	**0.988**
Malaysia	0	**0.065**	0.128	0.889	0	**0.021**	**0.061**	**0.971**	5	**0.924**	0.876	0.136	0	**0.038**	**0.097**	**0.938**
Philippines	0	**0.034**	**0.071**	**0.915**	0	**0.007**	**0.024**	**0.980**	0	**0.085**	0.157	0.870	0	**0.020**	**0.058**	**0.952**
Singapore	0	**0.080**	0.154	0.898	0	**0.024**	**0.071**	**0.966**	5	**0.902**	0.786	0.278	0	**0.049**	0.115	**0.941**
Thailand	0	**0.024**	**0.058**	**0.931**	0	**0.006**	**0.025**	**0.982**	0	**0.071**	0.144	**0.903**	0	**0.014**	**0.047**	**0.960**
U.S	0	0.105	0.182	0.879	0	**0.035**	**0.088**	**0.955**	5	0.816	0.731	0.234	0	**0.071**	0.142	0.921
$m = 10$																
Indonesia	0	0.197	0.303	0.411	0	0.105	0.227	0.589	0	0.204	0.360	0.439	0	0.176	0.307	0.447
Japan	1	**0.006**	**0.055**	**0.932**	0	**0.092**	0.330	0.790	1	**0.009**	0.104	**0.936**	0	0.131	0.400	0.722
Korea	0	**0.038**	0.140	0.833	0	**0.015**	0.102	**0.921**	0	**0.075**	0.223	0.806	0	**0.029**	0.140	0.868
Malaysia	0	**0.049**	0.165	0.810	0	**0.019**	0.117	**0.912**	5	0.378	0.167	0.719	0	**0.035**	0.163	0.867
Philippines	0	**0.051**	0.144	0.791	0	**0.014**	**0.094**	**0.903**	0	**0.076**	0.225	0.774	0	**0.036**	0.143	0.838
Singapore	0	0.130	0.278	0.689	0	**0.054**	0.186	0.838	5	0.471	0.227	0.642	0	**0.099**	0.259	0.754
Thailand	0	**0.084**	0.198	0.683	0	**0.036**	0.138	0.831	0	0.132	0.317	0.685	0	**0.066**	0.199	0.758
U.S	0	0.188	0.318	0.608	0	**0.069**	0.203	0.814	5	0.522	0.206	0.474	0	0.134	0.293	0.706
$m = 15$																
Indonesia	0	0.343	0.543	0.331	0	0.188	0.402	0.510	0	0.575	0.745	0.195	0	0.291	0.545	0.404
Japan	1	**0.046**	0.140	0.885	0	0.370	0.549	0.726	1	0.123	0.282	0.772	0	0.464	0.644	0.713
Korea	0	0.145	0.331	0.638	0	**0.056**	0.234	0.795	0	0.456	0.616	0.373	0	0.116	0.328	0.705
Malaysia	0	0.310	0.499	0.531	0	0.139	0.335	0.710	5	0.605	**0.047**	0.751	0	0.234	0.452	0.633
Philippines	0	0.193	0.381	0.551	0	**0.073**	0.245	0.743	0	0.517	0.669	0.316	0	0.138	0.348	0.648
Singapore	0	0.548	0.631	0.293	0	0.221	0.411	0.633	5	0.605	**0.024**	0.683	0	0.344	0.543	0.565
Thailand	0	0.280	0.465	0.491	0	0.114	0.307	0.686	0	0.618	0.752	0.275	0	0.182	0.406	0.611
U.S	0	0.431	0.607	0.531	0	0.195	0.397	0.718	5	0.604	0.484	0.748	0	0.296	0.529	0.652

P is the order of the ADF auxiliary regression obtained by AIC and the initial values have been taken from the actual series. Reported are the simulated p-values associated with the tests $t(m)$, $A(m)$, and $F(m)$ obtained using EasyReg International by Bierens. Rejections of the null hypothesis are reported in bold. Bierens argues that there is no unique way to select the order m; therefore, results for different values of m are reported.

Bierens' (1997) test alternative hypotheses

Test	Left-side rejection	Right-side rejection
$t(m)$	MS, LTS or NLTS	NLTS
$A(m)$	MS, LTS or NLTS	NLTS
$F(m)$		MS, LTS or NLTS

Note: MS=mean stationary, LTS=linear trend stationary, NLTS=nonlinear trend stationary. The $F(m)$ test is only right-side test.

Figure 1: Real oil prices in domestic currency