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Dynamics of the Real Exchange Rate in European Emerging Economies: Evidence from Quantile Regression

Summary: The sustainability of purchasing power parity (PPP) theory is examined within the quantile autoregression model for the monthly data of the euro- and the US dollar-based real exchange rate (RER) in selected European economies (the Czech Republic, Hungary, Poland, Romania, Serbia and Turkey). Period from January 2000 to December 2014 is covered. The application of quantile autoregression model is motivated by the necessity of identifying asymmetric behavior of the RER due to the shocks of different size and sign. The empirical results support to some extent the PPP theory for the euro- and US dollar-based RER in Romania, Serbia, and Turkey. The euro-based RER in Hungary and Poland is also identified to confirm the PPP theory. The dynamics of the RER in the Czech Republic cannot be associated with the PPP validity. The persistence of the euro-based RER is estimated to be more prominent after the depreciation shocks of smaller size.

Key words: Purchasing power parity, Real exchange rate, Quantile regression model.

JEL: C22, F31, F41.

A number of econometric studies are focused on testing the sustainability of PPP theory in the long-run. Assumption that dynamics adjustment is stable, regardless of the size of the shock and its impact on the distance of the RER from the equilibrium level, is increasingly viewed as one of the main reasons for the PPP hypothesis rejection. In fact, the considerable asymmetry in the adjustment of the RER is empirically confirmed in a number of articles (Mark P. Taylor, David A. Peel, and Lucio Sarno 2001; Bernd Schnatz 2006; Hassan Shirvani and Natalya Delcoure 2012). Such asymmetry implies that the smaller size of the shocks causes significant persistence of the RER, whereas the rate of return to equilibrium PPP level is disproportionally faster after greater shocks resulted in far more serious deviations.

Different econometric techniques are applied in empirical literature to take care of peculiar RER dynamics. Quantile approach based on quantile autoregressive model (QAR) and quantile unit root tests is one of them (Roger Koenker and Zhijie Xiao 2004, 2006). In contrast to the tests related to the analysis of the average behavior of the RER which are based on the assumption of constant mean-reverting process regardless of the type of shock, the motivation for the implementation of the QAR model

comes from the need of considering how shocks of different size and sign influence the movement of the RER. From the economic point of view, it is relevant to determine the degree of the RER persistence to accurately define the causes of deviations from the equilibrium level. In particular, the high persistence is mainly due to real shocks (such as technological shocks or productivity shocks), whereas, for example, changes in monetary policy can be manifested through aggregate demand shocks and cause little persistence of the RER and faster return to the long-term level (Kenneth Rogoff 1996; Sarno 2005). Thus, through application of QAR model, asymmetry in the RER persistence at each quantile is monitored which may help in assessing whether RER complies with equilibrium PPP level or not. From a statistical point of view, quantile framework is suitable for the analysis of time series whose empirical distribution is characterized by heavy tails, and it is non-Gaussian. This is frequently the case with the RER series.

In this article, we applied QAR model with the aim of capturing dynamics of the euro- and US dollar-based RER for the Czech Republic, Hungary, Poland, Romania, Serbia and Turkey during January 2000 to December 2014. Our sample consists of heterogeneous emerging European economies that are characterized by different levels of development and also different exchange rate regimes. Period considered includes negative macroeconomic trends caused by the global economic crisis. It is of interest to find out how RER reacts to shocks under different economic policy regimes given the substantial influence of great recession. In this way, asymmetric response of RER to unexpected shocks of various sizes may be identified.

Although the empirical validity of the PPP theory in the emerging European countries has been assessed frequently in recent past (among others: Juan C. Cuestas 2009; Erdinç Telatar and Mübariz Hasanov 2009; Saadet Kasman, Adnan Kasman, and Duygu Ayhan 2010; Robert J. Sonora and Josip Tica 2010; Alper Aslan and Ferit Kula 2011; Ahmad Zubaidi Baharumshah, Jani Bekő, and Darja Boršič 2011; Giray Gozgor 2011; Yang-Cheng Ralph Lu, Tsangyao Chang, and Chia-Hao Lee 2012; Veli Yilanci 2012; Václav Žďárek 2012; Huizhen He and Chang 2013; Zorica Mladenović, Kosta Josifidis, and Slađana Srdić 2013; Oguz Ocal 2013; Tolga Omay, Mubariz Hasanov, and Furkan Emirmahmutoglu 2014; Mohsen Bahmani-Oskooee and Chang 2015; Gianna Boero, Kostas Mavromatis, and Taylor 2015), the quantile methodology was only used in a recent article of Bahmani-Oskooee et al. (2016). In Bahmani-Oskooee et al. (2016), only US dollar-based RER are considered. Apart from implementing standard quantile approach, modification that accounts for structural breaks is also applied.

In this article, we use both the euro- and the US dollar-based RER. Interest in examining the euro-based real exchange rate comes from the fact that in our sample, four countries (the Czech Republic, Hungary, Poland and Romania) have became EU members during the observed period which makes the issue of real and nominal convergence with other EU economies increasingly relevant. The other two countries from our sample (Serbia and Turkey) are the candidate countries for the accession to the EU with high level of trade and financial integration with the EU member states. We intend to measure the reaction of the RER to the observed shocks that are endogenously identified by the model (cf. Kleopatra Nikolaou 2008) which has not been previously

performed when these countries are considered. All shocks are relevant for the purpose of our analysis, and therefore, we do not explicitly introduce structural break in modeling. In such a way, we assess the role of the actual shocks to the RER movements.

The rest of the article is structured as follows. After the introduction, Section 1 presents literature review based on quantile framework. Section 2 briefly explains the specifications of QAR model and quantile unit root test. In Section 3, preliminary data analysis is provided. Section 4 elaborates on the empirical results of applying QAR model, and Section 5 provides final findings about the sustainability of the PPP theory.

1. Literature Review

Quantile approach has been followed in a number of empirical papers to address the issue of RER dynamics. Developed economies are mostly covered. Some results are summarized below.

Analyzing the movement of the RER in the Euro area, the UK and Japan for a period 1973:01-2004:12, Nikolaou (2008) confirms that the RER exhibits different behavior across quantiles. The value of the autoregressive coefficient is close to unity on the medium quantiles, whereas for the extreme quantiles (upper and lower), the null hypothesis can be rejected. It is believed that the ability of the RER to recover to a level that ensures a balance in the long-term within certain quantile is sufficient to ensure stationarity of the entire process. Antonio F. Galvao Jr. (2009) finds similar conclusion for Canada, Japan, Switzerland, and the United Kingdom during the period of January 1973 to January 2007.

QAR models are also used to investigate the asymmetry in the return dynamics due to currency appreciation or depreciation of the following daily exchange rates: USD/EUR, USD/JPY, USD/GBP, USD/AUD, USD/CHF and USD/CAD from 1999 to 2014. The results of the research in the article of Konstantin Kuck, Robert Maderitsch, and Karsten Schweikert (2015) indicate that for most exchange rates, the US dollar depreciation refers to the negative dependence on past returns, whereas a positive dependence on past returns occurred after the appreciation. This tendency is explained by the presence of various factors on the international market, such as incomplete information about the currency movements, central bank interventions, currency carry trade, capital flows, activities of market participants vulnerable to the risk. Quantile models are furthermore suitable for the analysis of the dynamics of the RER under different exchange rate regimes. Applying the quantile unit root test to the data of the RER of New Taiwan Dollar from 1974 to 2008, Luke Lin and Wenyuan Lin (2013) point out the validity of PPP theory in circumstances of applying a fixed regime, whereas the implementation of a managed float regime can induce only partial compliance with the PPP level. The results in the article of Mauro S. Ferreira (2011), which are based on the behavior of pair wise RER between the Italian lira, French franc, Deutsch mark and British pound from January 1973 to December 1998 also show adequate implementation of QAR model in the case of the presence of heteroskedastic time series and different expectations about the RER movements.

Application of quantile approach proved to be appropriate in the case of the analysis of condition between the RER and economic growth, where the empirical findings in the work of Fabrício J. Missio et al. (2013) confirm the existence of a

nonlinear relationship, which is particularly obvious in developing and emerging countries and Eurozone during the period from 1978 to 2007.

Bahmani-Oskooee et al. (2016) support the sustainability of PPP theory in seven transition countries (Bulgaria, the Czech Republic, Hungary, Lithuania, Poland, Romania and Russia) during the period of 1998 to 2015, with calculated half-life estimates in the range of 12 to 25 months. The empirical findings justify the application of the extended version of the quantile unit root test that involves the inclusion of stationary covariates. Additionally, unit root approach that takes into account sharp shifts and smooth breaks in time series confirms the result that shocks responsible for the movement of the RER had predominantly temporary effects.

2. Quantile Autoregression (QAR) Model

This section shortly summarizes theoretical results on baseline QAR model and quantile unit root tests as defined in Koenker and Xiao (2004, 2006).

2.1 Specification of QAR Model

With the aim of performing QAR(1) model, we start from the first-order autoregression model:

$$y_t = \alpha_1 y_{t-1} + e_t. \tag{1}$$

The equivalent τ-th quantile representation takes the form:

$$Q_{yt}(\tau|y_{t-1}) = Q_e(\tau) + \alpha_1 y_{t-1}, \tag{2}$$

where $Q_e(\tau)$ denotes the τ-quantile of an error-term e_t, and $Q_{yt}(\tau|y_{t-1})$ is the τ-th conditional quantile of time series y_t conditional on y_{t-1} (Koenker and Xiao 2004). Component $Q_e(\tau)$ includes the impact of unanticipated shocks of different size that cause fluctuations in the movement of the observed time series, whereas quantiles absorb shocks from period t-1 to period t (Nikolaou 2008).

To define alternative form of QAR model, the following relations are established: $\alpha_0(\tau) = Q_e(\tau)$, $\alpha_1(\tau) = \alpha_1$ and define $\alpha(\tau) = (\alpha_0(\tau), \alpha_1(\tau))'$ and $x_t = (1, y_{t-1})'$. Therefore, $\alpha_1(\tau)$ is the autoregressive coefficient which evaluates the persistence of deviations of the observed time series within each quantile of interest. QAR(1) can be represented as:

$$Q_{yt}(\tau|y_{t-1}) = x_t'\alpha(\tau). \tag{3}$$

Estimation of the linear QAR model involves solving the problem:

$$\min_{\alpha \in \Re^2} \sum_{t=1}^n \rho_\tau(y_t - x_t'\alpha(\tau)), \tag{4}$$

where $\rho_\tau(e) = e(\tau - I(e < 0))$, whereas I denotes an indicator function which takes the value one if the expression in parentheses is true and zero otherwise.

The process of obtaining estimation of the QAR model presents a variation of the least absolute deviation (LAD) method, where Equation (4) can be written as:

$$\min_{\alpha \in \Re^2} \sum_{t:y_t \geq x_t'\alpha(\tau)} \tau(y_t - x_t'\alpha(\tau)) + \sum_{t:y_t < x_t'\alpha(\tau)} (\tau-1)(y_t - x_t'\alpha(\tau)). \tag{5}$$

This method is based on minimizing the least absolute deviations and is considered to be more appropriate for distribution with heavy tails (Koenker and Gilbert Bassett Jr. 1978; Seppo Pynnönen and Timo Salmi 1994).

2.2 Quantile Unit Root Test

Final conclusion on the existence of a unit root in time series y_t depends on the value of the parameter α_1. Under the null hypothesis $\alpha_1 = 1$, y_t has a unit root, and it is characterized by high level of persistence, while for the values $\alpha_1 < 1$ under the alternative hypothesis, observed time series is stationary. If there is autocorrelation up to order $q + 1$, Equation (1) is augmented by explanatory variables $\Delta y_{t-1}, ..., \Delta y_{t-q}$.

Hypotheses and modification for autocorrelation remain the same under the quantile unit root testing. For the inference on the unit root presence on quantile τ, the following t-statistic is considered (Koenker and Xiao 2004, 2006):

$$t_n(\tau) = \frac{f(\hat{F}^{-1}(\tau))}{\sqrt{\tau(1-\tau)}} (Y'_{-1} P_x Y_{-1})^{1/2} (\hat{\alpha}_1(\tau) - 1), \tag{6}$$

where $f(\hat{F}^{-1}(\tau))$ is a consistent estimator of $f(F^{-1}(\tau))$, and f and F represent the density and distribution function of e_t. Vector of lagged values of the dependent variable $\delta = \delta(\tau) = \frac{\sigma_{\omega\psi}(\tau)}{\sigma_\omega \sigma_\psi(\tau)} = \frac{\sigma_{\omega\psi}(\tau)}{\sigma_\omega \sqrt{\tau(1-\tau)}}$ is denoted by Y_{-1}, and P_x is the projection matrix onto the space orthogonal to $X = (1, \Delta y_{t-1}, ..., \Delta y_{t-q})$.

Using the test statistic $t_n(\tau)$ provides a comprehensive insight into the dynamics of the observed time series and provides framework for examining its mean-reverting properties at each quantile. This is in contrast with ordinary unit root test that only deals with conditional central tendency (Ching-Chuan Tsong and Cheng-Feng Lee 2011).

The limiting distribution of statistic (6) is nonstandard (Koenker and Xiao 2004, 2006). To accommodate for the small sample when critical values are calculated, resampling algorithms proposed by Koenker and Xiao (2004) may be followed.

Test statistic (6) can be calculated from the regression that incorporates stationary explanatory variables (Galvao Jr. 2009) that is in line with modified ADF test of Graham Elliott and Michael Jansson (2003). Limiting distribution of test statistic derived from such a regression is the same as that of (6).

Apart from test statistic (6), the presence of quantile unit root can also be assessed by looking at a range of quantiles. For that purpose, quantile Kolmogorov-Smirnov test is advanced taking the following form $sup|t_n(\tau)|, \tau \in T$ and T is total range of quantiles (Koenker and Xiao 2004). Its statistic is nonstandard with the possibility of determining critical values by simulation methods.

3. Empirical Results: Data Analysis and Preliminary Tests

We analyzed the sustainability of PPP theory in the following emerging European countries: the Czech Republic, Poland, Hungary, Romania, Serbia and Turkey, during the period of January 2000 to December 2014 (due to unfavorable developments during the 1990s, analysis for Serbia covers the period January 2001 to December 2014).

The data are downloaded from the Vienna Institute for International Economic Studies (2017)[1] and analyzed using the software packages E-Views, R and RATS. The time series of the RER is formed using the logarithm of monthly data for: nominal exchange rate (e_t) and the consumer price index (CPI) within individual countries (p_t^*), the Eurozone or the US market (p_t):

$$rer_t = e_t - p_t^* + p_t. \tag{7}$$

Since the Czech Republic, Hungary, Poland and Romania became EU members during the observed period, and all EU member states are also part of the economic and monetary union, interest in studying the euro-based real exchange rate has become increasingly prominent. On the other side, recognizing the connection of national currencies with euro as well as the high level of trade and financial integration with the member states, there is a clear need to analyze the real exchange rate in the candidate countries for accession to the EU (Serbia and Turkey). At the same time, testing the sustainability of the PPP theory for both the euro- and the US dollar-based real exchange rate is relevant given the international importance of the two leading currencies, as well as their dominance in the world trade.

The first part of the empirical results refers to the graphic illustration of the time series (Figures 1 and 2), followed by the analysis of normality. Formal testing of the presence of unit roots is based on the application of standard tests: ADF, Kwiatkowski-Phillips-Schmidt-Shin (KPSS), and Elliott-Rothenberg-Stock (ERS) and tests that take into account nonlinear dynamics (Kapetanios-Shin-Snell and Kruse). The second part of the econometric research relates to the representation of empirical findings obtained from the application of two parametric tests and QAR approach. Thereafter, we calculated half-life parameters for those quantiles where the hypothesis of the existence of a unit root is rejected.

Graphical presentation of the time series clearly indicates the alternation between periods of growth and decline of the RER, which has been especially pronounced since 2008, when adverse circumstances at the international level resulted in serious distortions. Looking at the countries that joined the EU in 2004 (the Czech Republic, Hungary, Poland), different waves of appreciation of the RER are evident until 2008. The Czech Republic has suffered two abrupt appreciation of the Czech Koruna. The first one occurred in 2002 due to a large capital inflow, whereas the second one is associated with the beginning of the global financial crisis in 2007. In the case of Poland, the currency was characterized by a sharp real depreciation from July 2008 to March 2009, which was highly related to serious economic downturn in the world economy and the outflow of foreign capital from Poland. On the other hand, Hungary and Romania have changed the exchange rate regime during the observed period, which was manifested in shifts of the RER as shown in Figure 1. Although Hungary had a long-term strategy of adapting the euro, the Hungarian government in 2008 decided to begin with the implementation of freely floating exchange rate regime due to the impossibility of maintaining its currency in defined margins of fluctuation. Also, since 2005, Romania has applied a policy of flexible exchange rate regime in

combination with direct inflation targeting. Despite significant interventions by monetary authorities with the aim of stabilizing the exchange rate, the Romanian leu suffered a significant depreciation during the period from July 2007 to February 2009 when it lost 40% of its value.
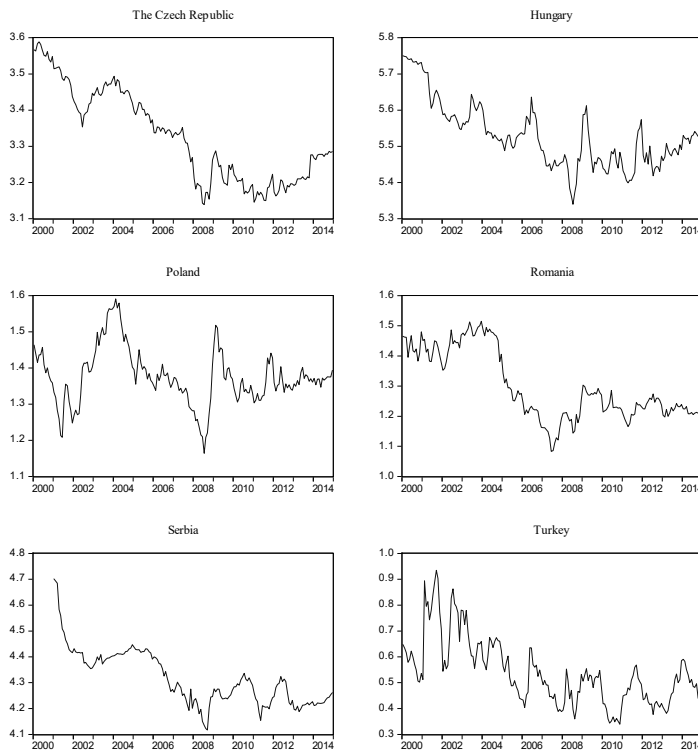
Source: Authors' estimations.

Figure 1 Euro-Based RER Movements in Selected Economies

Considering the RER of countries which are outside the EU, the high volatility of the Turkish lira is evident, which is characterized by a periods of sharp depreciation and significant loss of its value against the dollar and euro. When we talk about Serbia, the transition process (privatization and liberalization of capital and commodity transactions) and excessive government borrowing caused the capital inflows that have contributed to the appreciation of the currency in the period 2003 to 2008. In contrast, the reduction of foreign currency on the domestic market, due to lower investments and loans, resulted in a depreciation of the currency since 2008.

Source: Authors' estimations.

Figure 2 US Dollar-Based RER Movements in Selected Economies

Dynamics of corresponding nominal exchange rates are depicted in the Appendix (Figures A1 and A2). Subsamples of nominal depreciations and appreciations are evident, but no preliminary conclusion about the PPP validity can be drawn.

Based on the descriptive statistics[2], we can conclude that the distribution of the euro- and US dollar-based RER is characterized by right asymmetry, which is in most cases significantly different than zero. The values of the kurtosis indicate that three time series have heavy tails, two have thinner tails, and one is characterized by tails that correspond to the tails of normal distribution. Similar conclusions are derived for the US dollar-based RER. The calculated values of the Jarque-Bera statistics suggest that the null hypothesis of normality is rejected for all time series, except for US dollar-based RER for Poland. This supports the use of QAR model.

The empirical results of the applied unit root tests indicate that the hypothesis of stationarity is rejected for all of the observed economies except for the euro-based RER for Poland (Table 1)[3].

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[2] Descriptive statistics and analysis of normality are not reported to preserve space, but they are available from the authors upon request.

[3] Results of the ADF, KPSS and ERS for the first difference are not reported, but they are available from the authors upon request.

Table 1 Unit Root Tests (Level of the Time Series)

Selected economies	Euro-based RER				US dollar-based RER			
	k	ADF	KPSS	ERS	k	ADF	KPSS	ERS
The Czech Republic	0	-1.88	1.48	-0.13	0	-1.70	1.39	-0.33
Hungary	8	-2.83	1.15	-0.76	0	-1.94	1.17	-0.63
Poland	1	-3.08	0.19	-2.24	1	-2.11	1.16	-0.94
Romania	5	-1.50	1.13	-0.58	0	-1.53	1.27	-0.35
Serbia	5	-2.22	1.25	0.15	7	-2.48	1.15	-0.04
Turkey	0	-2.86	1.12	-2.27	0	-1.67	1.22	-0.87

Notes: Number of lags included to take care of the autocorrelation is denoted by k. Tests with constant as only deterministic components are used. The 5% critical values are -2.88, 0.46, -1.94 for ADF, KPSS and ERS test, respectively.

Source: Authors' calculations.

Because traditional unit root test may be invalid when data exhibit nonlinearity, we perform the nonlinear unit root tests developed by George Kapetanios, Yongcheol Shin, and Andy Snell (2003) and Robinson Kruse (2011). They are devised to test the unit root hypothesis against the alternative of stationary exponential smooth transition autoregression model. Such an alternative may be relevant for RER data because it assumes that time series is unit root process if it is close to its long-run equilibrium level from the previous period, whereas mean-reverting behavior appears when there is a certain departure from this equilibrium (Kruse 2011). The results are given in Table 2.

Table 2 Unit Root Testing against the Alternative of Stationary Exponential Smooth Transition Autoregression Model

Selected economies	Test							
	Kapetanios et al. (2003)				Kruse (2011)			
	Euro-based RER		US dollar-based RER		Euro-based RER		US dollar-based RER	
	k		k		k		K	
The Czech Republic	0	-2.12	0	-1.40	0	8.08	0	3.16
Hungary	8	**-2.78**	0	-1.32	8	6.81	0	6.31
Poland	1	-2.50	1	-1.30	1	5.66	0	1.73
Romania	5	-1.17	0	-2.56	5	1.43	0	**10.28**
Serbia	5	**-4.22**	7	**-2.71**	5	**22.92**	7	7.45
Turkey	0	**-3.12**	0	**-2.76**	0	7.8	0	8.40

Notes: Number of lags included to take care of the autocorrelation is denoted by k. Test with constant as only deterministic component is used. For the Kapetanios-Shin-Snell test, the 5% and the 10% critical values are -2.93 and -2.66, respectively. For the Kruse test, the 5% and the 10% critical values are 10.17 and 8.60, respectively. Significant values are in bold.

Source: Authors' calculations.

The unit root hypothesis against the alternative of stationarity with specific non-linear dynamics has been rejected for Serbia, Turkey, Hungary and Romania by at least one version of the tests. This hypothesis is again accepted for data in the Czech Republic and Poland. These findings suggest that movements in the RER cannot be clearly described by the unit root path in most of the economies considered when non-linear adjustment is taken into account. Quantile approach emerges as a next step as it looks at different quantiles of RER and shocks of different size.

4. Empirical Results: Quantile Estimations

We have tested for the presence of quantile unit roots by test-statistic (6) that was computed in two ways. First, QAR(1) model is used. Second, to compute the Galvao version, QAR(1) model is enlarged by covariate that should be stationary and correlated with the shocks to the RER (Galvao Jr. 2009). Our choices were inflation rate and depreciation rate. They were included at different lags. Because results are similar, we present results based on lagged-one inflation rate[4]. Table 3 contains testing results.

Table 3 Quantile Unit Root Test

■ **The Czech Republic**

Euro-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	-0.01336	0.89	0.99729	-0.09	0.93	0.00235	0.98	0.99301	-0.24	0.81
0.2	0.03669	0.47	0.98505	-0.99	0.32	0.06826	0.20	0.97594	-1.57	0.12
0.3	0.06146	0.10	0.97918	-1.78	0.08**	0.06662	0.06	0.97778	-2.07	0.04*
0.4	0.04418	0.13	0.98548	-1.64	0.10**	0.04286	0.19	0.98586	-1.44	0.15
0.5	0.05316	0.14	0.98346	-1.59	0.11	0.05220	0.19	0.98392	-1.31	0.19
0.6	0.06193	0.10	0.98201	-1.62	0.11	0.05553	0.20	0.98415	-1.23	0.22
0.7	0.06839	0.09	0.98110	-1.60	0.11	0.04483	0.29	0.98837	-0.98	0.33
0.8	0.07785	0.15	0.97964	-1.25	0.21	0.08376	0.12	0.97848	-1.37	0.17
0.9	0.09271	0.25	0.97710	-1.00	0.32	0.06549	0.35	0.98568	-0.67	0.51

US dollar-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	-0.09242	0.09	1.01408	0.83	0.41	-0.07265	0.21	1.00724	0.40	0.69
0.2	0.01099	0.77	0.98612	-1.22	0.23	0.00980	0.81	0.98650	-1.07	0.29
0.3	0.04704	0.23	0.97781	-1.77	0.08**	0.04511	0.27	0.97898	-1.70	0.09**
0.4	0.02450	0.63	0.98739	-0.76	0.45	0.02993	0.54	0.98562	-0.87	0.39
0.5	0.01785	0.73	0.99355	-0.39	0.70	0.01863	0.74	0.99343	-0.36	0.72
0.6	0.05032	0.20	0.98591	-1.23	0.22	0.03797	0.38	0.98927	-0.81	0.42
0.7	0.06725	0.21	0.98326	-0.96	0.34	0.06763	0.24	0.98316	-0.92	0.36
0.8	0.05703	0.40	0.99003	-0.49	0.63	0.06885	0.31	0.98684	-0.60	0.55
0.9	0.11307	0.11	0.97798	-0.98	0.33	0.10321	0.15	0.98236	-0.85	0.40

■ **Hungary**

Euro-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	0.18222	0.57	0.96182	-0.66	0.51	-0.00251	0.99	0.99663	-0.06	0.95
0.2	0.01728	0.91	0.99395	-0.21	0.84	0.04780	0.76	0.98884	-0.40	0.69
0.3	-0.00451	0.97	0.99977	-0.05	0.96	0.10730	0.49	0.97887	-0.73	0.46
0.4	0.05011	0.63	0.98977	-0.53	0.60	0.03520	0.81	0.99265	-0.28	0.78
0.5	0.11872	0.24	0.97802	-1.16	0.25	0.10609	0.37	0.98074	-0.89	0.38
0.6	0.16331	0.08	0.97105	-1.68	0.10**	0.11938	0.29	0.97926	-1.05	0.30
0.7	0.25931	0.01	0.95464	-2.75	0.01*	0.15361	0.20	0.97416	-1.16	0.25
0.8	0.45253	0.00	0.92125	-5.50	0.00*	0.43779	0.00	0.92427	-3.25	0.00*
0.9	0.68592	0.00	0.88065	-5.19	0.00*	0.65988	0.00	0.88623	-5.20	0.00*

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[4] These results are available upon request.

US dollar-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	-0.04132	0.71	0.99878	-0.06	0.95	-0.03268	0.77	0.99649	-0.17	0.87
0.2	-0.02616	0.79	0.99874	-0.07	0.95	-0.01053	0.91	0.99606	-0.22	0.83
0.3	-0.02529	0.71	1.00049	0.04	0.97	-0.02217	0.74	1.00067	0.05	0.96
0.4	0.04618	0.52	0.98879	-0.88	0.38	0.05159	0.44	0.98866	-0.94	0.35
0.5	0.01235	0.86	0.99673	-0.26	0.79	0.01167	0.87	0.99709	-0.22	0.83
0.6	0.06401	0.42	0.98806	-0.85	0.39	0.06107	0.47	0.98889	-0.72	0.47
0.7	0.20884	0.04	0.96356	-1.99	0.05*	0.20283	0.05	0.96467	-1.77	0.08**
0.8	0.14833	0.20	0.97693	-1.04	0.30	0.18890	0.11	0.96957	-1.42	0.16
0.9	0.27342	0.08	0.95701	-1.47	0.14	0.32797	0.04	0.94639	-1.90	0.06**

Poland

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	0.04206	0.45	0.94773	-1.24	0.22	0.05672	0.42	0.94340	-1.17	0.24
0.2	0.06844	0.18	0.93417	-1.79	0.08**	0.03692	0.38	0.96076	-1.28	0.20
0.3	0.08246	0.11	0.92803	-1.92	0.06**	0.07217	0.17	0.93841	-1.62	0.11
0.4	0.08284	0.13	0.93249	-1.68	0.10**	0.10821	0.04	0.91743	-2.12	0.04*
0.5	0.05241	0.39	0.96012	-0.89	0.37	0.10055	0.08	0.92697	-1.79	0.08**
0.6	0.05577	0.33	0.96279	-0.87	0.39	0.04011	0.55	0.97560	-0.50	0.62
0.7	0.03836	0.49	0.98016	-0.49	0.63	0.07127	0.23	0.95774	-0.97	0.33
0.8	0.06454	0.30	0.96632	-0.80	0.42	0.06971	0.23	0.96528	-0.86	0.39
0.9	0.18490	0.00	0.89044	-2.29	0.02*	0.14671	0.04	0.92388	-1.48	0.14

US dollar-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	-0.03509	0.24	0.98582	-0.57	0.57	-0.02178	0.44	0.97847	-0.88	0.38
0.2	-0.01745	0.52	0.98512	-0.65	0.51	-0.02590	0.34	0.99623	-0.17	0.87
0.3	0.00097	0.97	0.97959	-0.98	0.33	0.00480	0.86	0.98375	-0.82	0.41
0.4	0.00177	0.94	0.98981	-0.52	0.60	0.00499	0.82	0.98925	-0.61	0.54
0.5	0.01326	0.51	0.98682	-0.82	0.41	0.01581	0.44	0.98584	-0.85	0.40
0.6	0.02573	0.33	0.98146	-0.90	0.37	0.02892	0.28	0.98272	-0.78	0.44
0.7	0.06383	0.04	0.95910	-1.65	0.10**	0.05872	0.07	0.96607	-1.26	0.21
0.8	0.07520	0.03	0.95901	-1.39	0.17	0.05001	0.15	0.98259	-0.62	0.53
0.9	0.11627	0.10	0.94043	-1.12	0.26	0.11773	0.09	0.93960	-1.15	0.25

Romania

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	0.08080	0.11	0.91501	-2.20	0.03*	0.08092	0.28	0.91491	-1.36	0.17
0.2	0.05938	0.05	0.94070	-2.27	0.02*	0.03113	0.31	0.96550	-1.29	0.20
0.3	0.05007	0.06	0.95313	-2.21	0.03*	0.03839	0.16	0.96306	-1.72	0.09**
0.4	0.02720	0.31	0.97548	-1.15	0.25	0.04485	0.07	0.96079	-1.94	0.05*
0.5	0.01991	0.20	0.98400	-1.08	0.28	0.02480	0.25	0.97928	-1.16	0.25
0.6	0.01311	0.56	0.99203	-0.45	0.66	0.01434	0.60	0.99078	-0.42	0.68
0.7	0.00480	0.84	1.00345	0.18	0.85	0.00521	0.87	1.00190	0.07	0.94
0.8	0.02774	0.36	0.98985	-0.42	0.67	0.04656	0.13	0.97225	-1.09	0.28
0.9	0.02106	0.64	1.00406	0.13	0.90	0.05300	0.15	0.97273	-0.92	0.36

US dollar-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	-0.08125	0.00	1.03852	2.45	0.02*	-0.05089	0.01	1.00016	0.01	0.99
0.2	-0.04530	0.00	1.01906	1.91	0.06**	-0.02928	0.07	0.99818	-0.11	0.92
0.3	-0.02594	0.02	1.00741	0.91	0.36	-0.02319	0.21	1.00278	0.14	0.89
0.4	-0.00946	0.33	0.99952	-0.06	0.95	0.00469	0.79	0.98351	-0.87	0.38
0.5	-0.00751	0.56	1.00306	0.29	0.77	0.00854	0.67	0.98367	-0.83	0.41
0.6	0.01191	0.42	0.99177	-0.78	0.44	0.02993	0.06	0.97140	-1.93	0.06**
0.7	0.03712	0.00	0.97714	-2.93	0.00*	0.05401	0.00	0.95944	-4.29	0.00*
0.8	0.05974	0.00	0.96413	-3.46	0.00*	0.06276	0.00	0.95702	-3.77	0.00*
0.9	0.11082	0.00	0.93467	-3.34	0.00*	0.11087	0.00	0.93477	-2.74	0.01*

■ **Serbia**

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	0.24615	0.25	0.93639	-1.24	0.22	0.00475	0.98	0.99360	-0.12	0.91
0.2	0.08109	0.56	0.97731	-0.77	0.44	0.00032	0.99	0.99731	-0.07	0.94
0.3	0.07326	0.40	0.98072	-0.97	0.33	0.02785	0.81	0.99229	-0.29	0.77
0.4	0.12845	0.09	0.96923	-1.82	0.07**	0.01104	0.88	0.99721	-0.16	0.88
0.5	0.10103	0.08	0.97661	-1.79	0.08**	0.06241	0.38	0.98579	-0.86	0.39
0.6	0.14531	0.00	0.96719	-3.30	0.00*	0.11611	0.08	0.97422	-1.83	0.07**
0.7	0.17249	0.00	0.96141	-3.33	0.00*	0.15776	0.04	0.96525	-1.94	0.05*
0.8	0.23176	0.00	0.94880	-2.94	0.00*	0.25806	0.01	0.94304	-2.46	0.01*
0.9	0.31979	0.03	0.93008	-2.10	0.04*	0.30672	0.13	0.93355	-1.43	0.05*

US dollar-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	0.02578	0.84	0.98160	-0.60	0.55	0.01106	0.93	0.98612	-0.43	0.67
0.2	0.08787	0.434	0.97062	-1.10	0.27	0.09433	0.42	0.97034	-1.06	0.29
0.3	0.13541	0.06	0.96206	-2.17	0.03*	0.14751	0.10	0.95951	-1.87	0.06**
0.4	0.13723	0.02	0.96303	-2.57	0.01*	0.14273	0.06	0.96221	-2.07	0.04*
0.5	0.14190	0.03	0.96479	-2.15	0.03*	0.13074	0.12	0.96764	-1.63	0.10**
0.6	0.16150	0.01	0.96251	-2.60	0.01*	0.17354	0.02	0.95959	-2.31	0.02*
0.7	0.16446	0.01	0.96275	-2.46	0.01*	0.18817	0.01	0.95660	-2.48	0.01*
0.8	0.20055	0.02	0.95646	-2.11	0.04*	0.25922	0.01	0.94148	-2.32	0.02*
0.9	0.20905	0.05	0.95787	-1.64	0.10**	0.30566	0.03	0.93361	-1.91	0.06**

■ **Turkey**

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	0.04561	0.02	0.82697	-4.62	0.00*	0.04638	0.01	0.82339	-4.29	0.00*
0.2	0.03657	0.03	0.86836	-3.85	0.00*	0.04012	0.02	0.85675	-4.17	0.00*
0.3	0.04117	0.02	0.87563	-3.67	0.00*	0.03463	0.04	0.89139	-3.26	0.00*
0.4	0.05183	0.02	0.87309	-2.92	0.00*	0.04300	0.03	0.89479	-2.62	0.01*
0.5	0.03388	0.05	0.92700	-2.15	0.03*	0.02680	0.15	0.94975	-1.18	0.24
0.6	0.03147	0.07	0.94857	-1.54	0.13	0.02558	0.12	0.96827	-0.87	0.38
0.7	0.03359	0.21	0.96280	-0.72	0.47	0.02283	0.40	0.98711	-0.23	0.82
0.8	0.01280	0.64	1.02771	0.53	0.60	0.02526	0.37	0.99950	-0.01	0.99
0.9	0.04983	0.01	0.99718	-0.08	0.94	0.04634	0.13	1.00502	0.08	0.94

US dollar-based RER

Quantile	Model without inflation					Model with inflation				
	$\alpha_0(\tau)$		$\alpha_1(\tau)$			$\alpha_0(\tau)$		$\alpha_1(\tau)$		
	Estimate	p-val.	Estimate	t-stat.	p-val.	Estimate	p-val.	Estimate	t-stat.	p-val.
0.1	-0.01919	0.10	0.90185	-2.24	0.03*	-0.02076	0.09	0.91295	-1.82	0.07**
0.2	-0.01992	0.00	0.95828	-1.97	0.05*	-0.01855	0.00	0.95959	-1.99	0.05*
0.3	-0.01321	0.01	0.96254	-1.97	0.05*	-0.01312	0.02	0.96469	-1.68	0.10**
0.4	-0.00918	0.12	0.98277	-0.90	0.37	-0.00958	0.16	0.98475	-0.74	0.46
0.5	-0.00455	0.52	0.98839	-0.66	0.51	-0.00559	0.43	0.99257	-0.36	0.72
0.6	0.00987	0.21	0.97639	-1.27	0.21	0.00851	0.27	0.97592	-1.02	0.31
0.7	0.01967	0.01	0.98194	-1.05	0.30	0.02083	0.00	0.97708	-1.07	0.29
0.8	0.02913	0.00	1.00036	0.01	0.99	0.02886	0.00	1.00363	0.12	0.91
0.9	0.05298	0.00	0.99882	-0.05	0.96	0.05633	0.00	1.00230	0.07	0.94

Notes: $\alpha_0(\tau)$ and $\alpha_1(\tau)$ denote the estimated values of the constant term and autoregressive coefficient respectively, for τ = (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9). For the slope coefficient we tested the null of a unit root (α_1 = 1) and bootstrapped *p*-values are calculated using the xy-pair method for 2000 replications. * and ** denote statistical significance at the 5% and 10% level, respectively.

Source: Authors' calculations.

As pointed out by Nikolaou (2008), a negative/positive sign of the parameters $\alpha_0(\tau)$ is actually negative/positive shock that has influenced the RER movement within the observed quantiles. Also, the negative shock can be interpreted as appreciation, positive as depreciation (Nikolaou 2008; Lin and Lin 2013).

A graphical illustration of the estimated parameters, $\alpha_0(\tau)$ and $\alpha_1(\tau)$, is presented below (Figures 3 and 4). Vertical axis shows the value of the estimated coefficients, whereas the horizontal represents individual quantiles. The gray areas indicate the 95% confidence band.
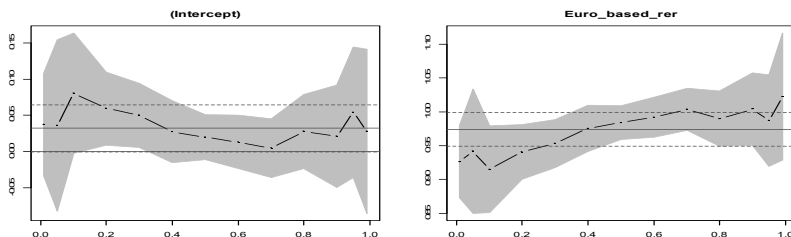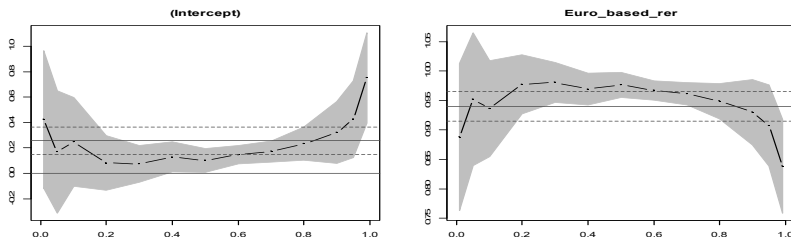
The Czech Republic
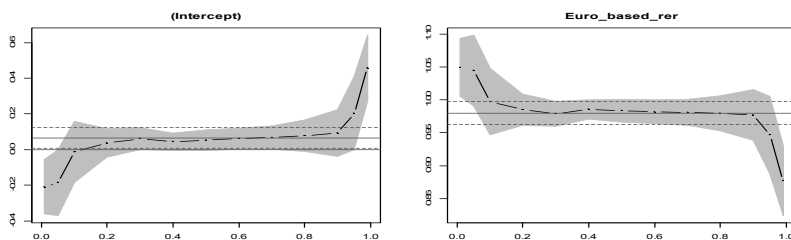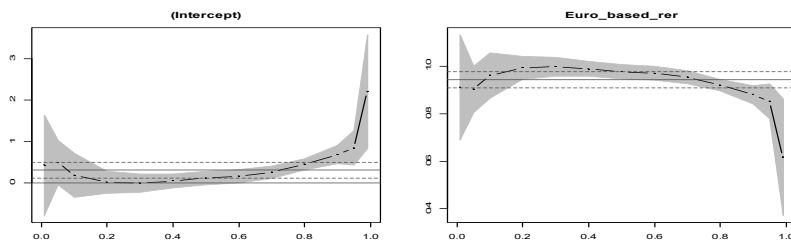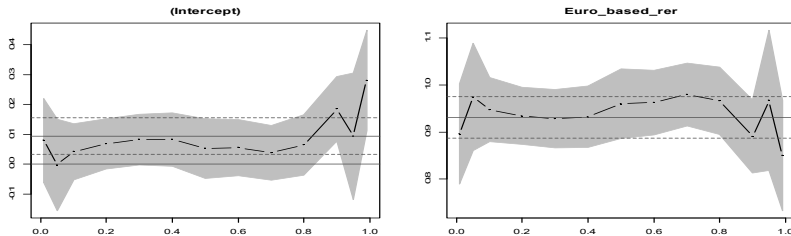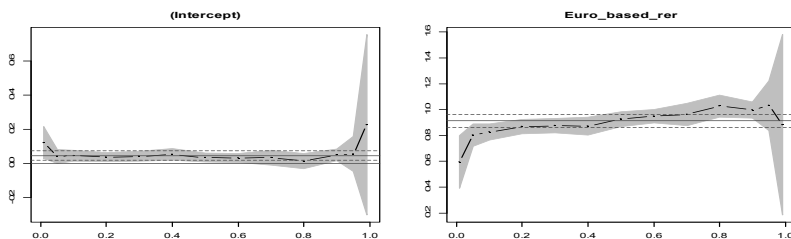

Hungary

Poland

Romania

Serbia

Turkey

Notes: The gray areas indicate the 95% confidence band obtained from the bootstrap replication set to be 2000.
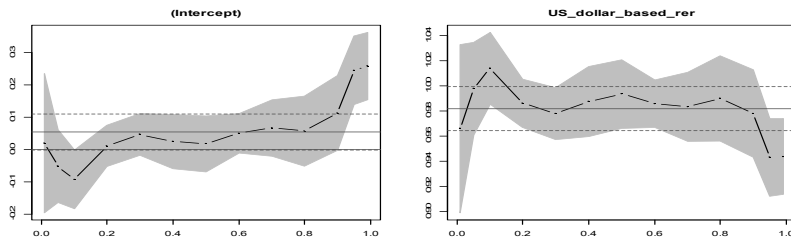
Source: Authors' estimations.

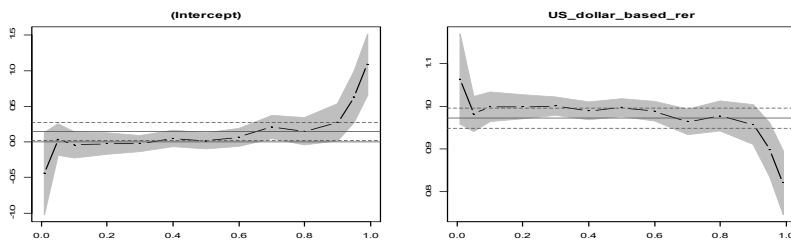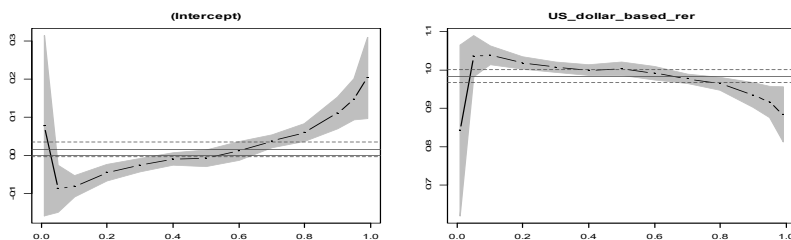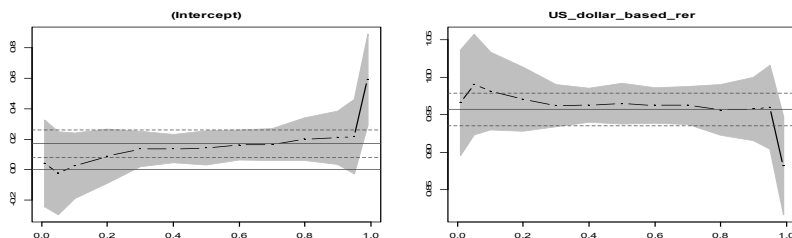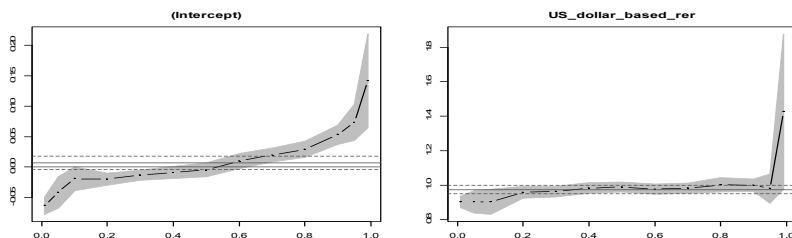**Figure 3** Estimated Parameters of the Quantile Regression for Euro-Based RER

We will now describe findings for the euro-based RER. Estimates of $\alpha_0(\tau)$ vary across different countries for a given quantile so that they do not follow identical path when all quantiles are considered. Only for the Czech Republic, monotonically increasing path is observed at all quantiles. In Hungary, similar increasing path is also detected, but for the quantiles from 0.4 on. For the lowest quantile, one of the biggest

shock has been estimated. For the RER in Poland, biggest shocks were estimated at the highest quantiles, but for the rest of the quantiles, we first have a sequence of relatively higher and then a sequence of relatively smaller values. In Romania, estimates of $\alpha_0(\tau)$ follow decreasing pattern with the highest value achieved at the lower quantile. Inverted U-shaped path is estimated for the Serbian data but with the bigger value attained at the higher quantile. In Turkey, peculiar pattern is found: two highest estimates are detected for the highest and for the lowest quantile, respectively, whereas in-between estimates follow a flat line.

The Czech Republic

Hungary

Poland

Romania

Serbia

Turkey

Notes: The gray areas indicate the 95% confidence band obtained from the bootstrap replication set to be 2000.

Figure 4 Estimated Parameters of the Quantile Regression for US Dollar-Based RER

We now turn to the values of the estimated autoregressive coefficients $\alpha_1(\tau)$. Given these estimates stationarity is mainly adapted at the extreme quantiles, which is confirmed by lower values of the estimated coefficients and the corresponding *p*-values at all or at a considerable number of quantiles. In Hungary and Serbia, mean-reverting occurs at higher quantiles upon huge depreciation shocks. In Poland, the euro-based RER stationarity is accepted for several lower and midquantiles that were characterized by relatively high positive shocks. Mean-reverting behavior of the RER is detected in Romania at low quantiles. However, at these quantiles, large depreciation shocks were achieved. Similarly, stationarity of the RER in Turkey is found for the first half of the lowest quantiles, but associated with relatively huge depreciation shocks.

Results for the US dollar-based data are to some extent different. First, estimates of $\alpha_0(\tau)$ follow similar pattern that can be described as monotonically increasing with the exception of Romania and Serbia for the lowest quantiles. The decision about the presence of a unit root in US dollar-based RER is strongly confirmed for the Czech Republic, Poland and Hungary. Such a conclusion may be questioned in the case of Serbia, Romania and Turkey. Stationarity of the US dollar-based RER is accepted for three lowest quantiles in Turkey. For Romania, mean-reverting behavior is found at the highest quantiles, whereas in Serbia, stationarity is not accepted only for the lowest quantiles.

Table 4 Estimation of Half-Life (in Months) for Euro- and US Dollar-Based RER

Quantile	Model without inflation											
	Euro-based RER						US dollar-based RER					
	The Czech Republic	Hungary	Poland	Romania	Serbia	Turkey	The Czech Republic	Hungary	Poland	Romania	Serbia	Turkey
0.1	∞	∞	∞	7.80	∞	3.65	∞	∞	∞	18.34	∞	6.71
0.2	∞	∞	10.18	11.34	∞	4.91	∞	∞	∞	36.71	∞	16.26
0.3	32.94	∞	9.28	14.44	∞	5.22	30.89	∞	∞	∞	17.92	18.16
0.4	47.39	∞	9.92	∞	22.18	5.11	∞	∞	∞	∞	18.40	∞
0.5	∞	∞	∞	∞	29.29	9.14	∞	∞	∞	∞	19.34	∞
0.6	38.18	23.60	∞	∞	20.78	∞	∞	∞	∞	∞	18.14	∞
0.7	∞	14.93	∞	∞	17.61	∞	∞	18.67	16.60	10.26	18.26	∞
0.8	∞	8.45	∞	∞	13.19	∞	∞	∞	∞	18.98	15.57	∞
0.9	∞	5.45	5.97	∞	9.56	∞	∞	∞	∞	10.26	16.10	∞

Notes: Half-lives are calculated using the formula: $\ln(0.5) / \ln(\alpha_1)$.

Source: Authors' calculations.

Estimates of half-lives derived from estimates of $\alpha_1(\tau)$ are given in Table 4[5]. According to the presented values in Table 4, we can conclude that, in general, the estimated half-lives are lower on the extreme quantiles relative to the middle quantiles, which in the case of the euro-based RER varied in the range of 3 to 13 months, whereas for the US dollar-based RER, they are slightly higher and shift in the interval between 6 and 18 months. Given our previous analysis of the shocks magnitude at different quantiles for the euro-based RER, it seems that greater depreciation shocks with serious deviations in the movement of the observed time series at the same time encourage faster alignment with the long-term PPP equilibrium. Such an adjustment occurred only at bigger quantiles in Hungary and Serbia, but only at lower quantiles in Romania and Turkey. In Poland, some low and medium quantiles are relevant for the adjustment. The US dollar RER exhibits stronger mean reverting adjustment at lower quantiles in Turkey as a result of the appreciation shocks. For the case of Serbia, adjustment is stronger at medium and high quantiles upon depreciation shock happened. Similarly, in Romania, mean reverting is found to be stronger at higher quantiles again after the depreciation shock.

Our empirical findings for the US dollar-based real exchange rate are broadly similar to the results of Bahmani-Oskooee et al. (2016) given the differences in the sample and the observation period. Because Bahmani-Oskooee et al. (2016) do not provide estimates of the actual shock size, $\alpha_0(\tau)$, results cannot be fully compared. Nevertheless, different findings concerning the PPP validity are obtained only in the case of the Czech Republic. For the other countries considered in both studies (Hungary, Poland and Romania) identical conclusion about the sustainability of PPP theory is reached. Also, the estimates of half-life are in the range of 1 to 2 year in both studies.

Although there are opposite views in the literature from the point of *de jure* and *de facto* applied exchange rate regime in selected countries (Ali Massoud and Julius Horvath 2015; International Monetary Fund 2016; Ethan Ilzetzki, Carmen M.

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[5] Estimated values of half-lives may be influenced by the weakness of quantile modelling known in the literature as quantile crossing, which implies lack of monotonicity in the estimation of conditional and structural quantiles. The application of the corrections for quantile crossing is beyond the scope of the paper. We thank an anonymous referee for pointing out this issue.

Reinhart, and Rogoff 2017), we can derive a general conclusion that countries considered have applied regime of more or less controlled fluctuations during most of the observed period. Given the fact that a flexible regime is characterized by the possibility of intervention in the foreign exchange market to prevent excessive oscillations of the exchange rate, it is evident that the shocks only have a temporary impact on the RER deviation with respect to the equilibrium level in the countries where PPP is sustainable. Therefore, it is assumed that in countries where the validity of the PPP theory is confirmed, nominal exchange rates had a greater role in restoring departures from long-term equilibrium. In the case of the euro-based RER, PPP theory has not been confirmed only for the Czech Republic: actually a long period of appreciation and external shocks have prevented the return of the RER to the equilibrium level. In terms of the US dollar-based RER, compliance of the RER with the PPP theory has been rejected for the Czech Republic, Hungary and Poland, also for the countries that joined the EU in 2004 while maintaining their own currencies with using the euro as reference currency.

Empirical results for the euro-based real exchange rate are in line with expectations, due to the fact that the currency of each country is highly associated with the euro, bearing in mind the significant degree of trade and financial integration between the EU member states. A similar conclusion holds for Serbia and Turkey, because a large part of the balance of payment transactions takes place on the European market.

5. Concluding Remarks

This article investigates the validity of PPP theory on a selected sample of emerging European economies: the Czech Republic, Hungary, Poland, Romania, Serbia and Turkey during the period of 2000 to 2014. To overcome the shortcomings of standard linear model econometric analysis, which does not take into account the possibility of different speeds of the RER adjustment, the QAR model is applied. It enables assessment of the different influences that high and low shocks may have on the RER dynamics. Thus, asymmetric reaction to shocks of different size may be more easily observed within the QAR model.

Application of three conventional unit root tests indicates the presence of a unit root in all time series of the US dollar-based RER. Similar findings were obtained for the euro-based RER.

However, under the framework of QAR model, we found that in most cases, the RER does not follow unit root process over different quantiles, because stationary was determined on a number of quantiles. For the US dollar-based RER, empirical validity of the PPP theory is confirmed for Romania, Serbia and Turkey. The same conclusion is reached not only for the euro-based RER in these economies but also in Hungary and Poland.

Half-life estimates derived from the euro-based RER imply that large positive shocks, which cause serious deviations in the RER movement toward depreciation, tend to induce stronger mean-reversion behavior. Such a pattern is detected at higher quantiles in Hungary and Serbia and at lower quantiles in Romania, Turkey and Poland. The persistence of the euro-based RER is estimated to be more prominent after the depreciation shocks of smaller size.

Different response of the euro-based RER to different size shocks may indicate that policy interventions were conducted depending on the size of misalignments. This is expected for these economies because they have been under the influence of various unanticipated impacts over the sample considered.

Quantile analysis of the US dollar-based RER in the Czech Republic, Hungary and Poland and additionally of the euro-based RER in the Czech Republic do not show regularity that would confirm the PPP validity. Mean-reverting behavior is accepted in Turkey for the lowest quantiles upon the hit of the appreciation shocks. For Romania and Serbia, the smallest half-life values were estimated at higher quantiles after the large depreciation shocks occurred.

PPP theory has not been supported only by the euro-based RER in the Czech Republic. This is due to the relatively long subsample of systematic appreciation and external shocks that have prevented the return of the RER to the equilibrium level in this economy. Compliance of the US dollar-based RER with the PPP theory has been rejected for those economies from our sample that joined the EU in 2004 while maintaining their own currencies with using the euro as reference currency.

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Appendix
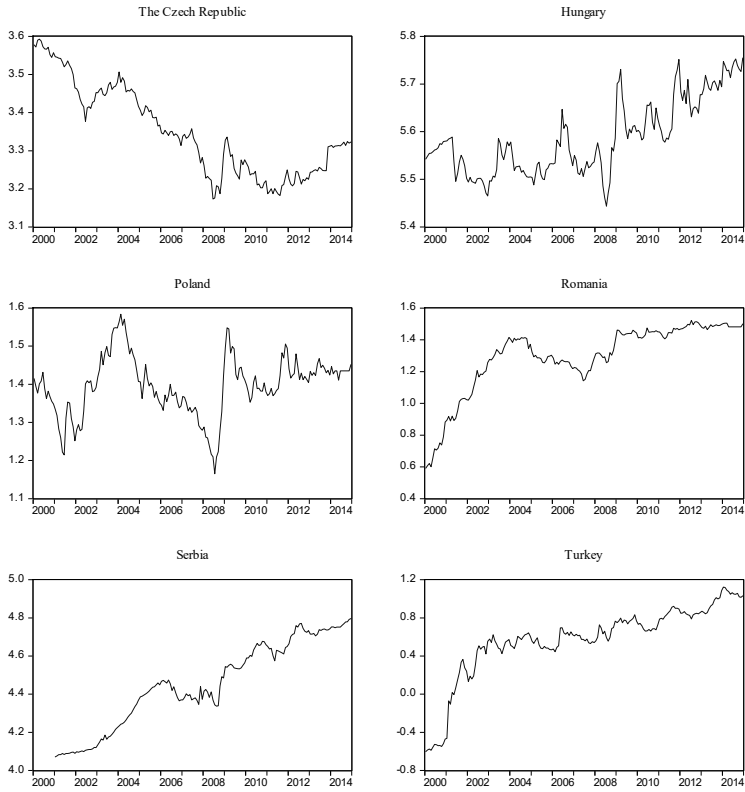
Source: Authors' estimations.

Figure A1 Euro-Based Nominal Exchange Rates

Figure A2 US Dollar-Based Nominal Exchange Rates