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Do financial markets in central and eastern European countries experience post-crisis mean reversion?

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Abstract

While several studies have examined the mean reversion of returns on equity markets in industrialized countries, there has been a lack of academic research on the markets of central and eastern European countries (CEECs). Our research aims to fill this gap by employing an innovative measurement method that uses an exponential moving average. The results indicate an absence of mean reversion in the very short term (daily horizon) but there are different effects on other investment horizons depending on the type of crisis. During the 2008 financial crisis and at the start of the war in Ukraine, the mean reversion effect was more noticeable in the medium term (90 days), while it was more marked in the short term (ten days) during the Covid-19 crisis.

none
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1. Introduction

Financial markets regularly face economic, political and social shocks, and react based on their expectations of what will happen after the event in question. When a shock proves to be small and short-lasting, investors quickly assess the potential consequences. However, when the shock is due to a national or global crisis, they try to determine whether there will be a return to a situation that can be described as usual or ordinary. The existence and speed of such a return constitutes major information for investors. Indeed, their strategy and the composition of their portfolios largely depend on this in order to extract potential abnormal returns on the financial markets.

As most stock markets have been affected by crises since the beginning of this century, it is interesting to analyse the reaction of stock markets that have not been the subject of much academic research and yet that are essential in the European Union, namely the stock markets of central and eastern Europe countries (CEECs). As these markets were not all open before the internet bubble burst in 2000, we focus our attention on crises that occurred after 2000. We therefore study the repercussions of the 2008 global financial crisis, the 2020 Covid-19 crisis and the geopolitical crisis linked to the war in Ukraine since 2022. Our research question is therefore: "To what extent do CEEC stock markets experience a mean reversion effect after a large-scale crisis". At the same time, we wish to identify how the reactions of CEECs to crises differ in general as well as how they differ in relation to the three crises under study, which, to our knowledge, has not been done until now.

To do this, we use various analysis tools, some of which have already been used on other markets for other analysis periods (Ljung-Box test, direct observation of daily price variations). We also performed an ARMA model, a Granger causality test to detect spillovers, and a mean reversion evaluation method based on differences between the medium-term memory and the short-term memory of the markets. This last approach, along with the focus on CEECs, which has not as yet drawn much attention, constitutes the methodological originality of this work.

This article is organized as follows. Section 2 reviews the literature, Section 3 details our methodology and tests, Section 4 presents the results and Section 5 concludes.

2. Literature review

De Bondt and Thaler (1985) were first to highlight the phenomenon of market overreactions after an event. They formalized the contrarian investment strategy, which entails buying securities that have lost value and selling securities that have gained value. This strategy is profitable when the markets overreact, in other words when an exaggerated price variation is followed by a correction, which is known as mean reversion. It is therefore important to detect the existence of such corrections in order to use them appropriately in an investment policy.

Fama and French (1988) measured the serial correlation of returns to determine the horizon of a momentum effect or of a mean reversion effect of stock returns. Poterba and Summers (1988) also showed that the variance of stock returns in the US market included a temporary component if there was a crisis over the period studied. They demonstrated a tendency towards the momentum effect in the short term and the mean reversion effect in the long term. Kim *et al.* (1991) considered the mean reversion in profitability to be low during the decades following World War II. Recent results for industrialized countries tend to conclude in favour of a mean reversion phenomenon on profitability. Kim and Kim (2018) compared the US and UK markets on the one hand and 16 industrialized or emerging markets on the other and noted a mean reversion in the UK market. Zakamulin (2016) focused on the very long term and concluded that mean reversion horizons ranged from 15 to 17 years in the American market. In an approach involving the Hurst exponent, Enow (2023) also concluded that there was a mean reversion for four markets (US, Japan, France and Germany) but not for the emerging market of South Africa. Considering European markets outside of the CEECs, Narayan and Prasad (2007) concluded that there was no mean reversion. Over the period from August 2019 to July 2020, Coskun *et al.* (2023) identified a weakening of the mean reversion effect after the start of the Covid-19 crisis, but their sample of 41 markets contained only four CEECs.

Using monthly data and therefore considering the very long term, Chaudhury and Wu (2003) concluded that there was no reversion to the mean for 17 emerging countries. Their study, however, did not include any CEECs and was sensitive to the currency used (local or USD) and the level of inflation, which created divergence in the results. In addition, their tests aimed to detect breaking points, whereas our approach is based on crises that have already been identified. In his study of ten frontier markets in the Middle East and North Africa, Neaime (2015), using traditional methods (augmented Dickey-Fuller and Phillips-Perron tests), showed that there was no reversion to the mean on daily data for the period from 2005 to 2014. Focusing on seven emerging Asian markets and essentially relying on generalized autoregressive conditional heteroskedasticity (GARCH) modelling, Ahmed *et al.* (2018) found divergent results related to the existence and duration of a reversion to the mean. Divergent conclusions can be observed even within a given country, as demonstrated by Palwasha *et al.* (2018) with their GARCH models tests on three indices of the Pakistan stock market.

The lack of homogeneity in the results according to the periods and countries studied, and the small amount of research relating to CEECs, therefore calls for an observation of these markets. This gap in the literature is particularly noticeable in relation to economies that experience phases of crises, as has been the case since 2008.

3. Methodology and data

3.1. Period under study and ARMA model

To conduct a comprehensive study, we consider all 17 CEEC stock markets, including those of Russia and Ukraine. Table i shows the main stock market indices, the number of firms listed in the indices and the market capitalization in July 2024.

Table i. CEEC stock indices studied

Country	Main index	Number of firms listed in the index	Market capitalization (billion USD) in July 2024
Bosnia	SESX10	10	5.2
Bulgaria	SOFIX	15	6.9
Croatia	CROBEX	25	26
Czech rep.	PX	10	21.4
Estonia	OMX Tallin	15	5.1
Hungary	BUX	16	43.8
Latvia	OMX Riga	20	5
Lithuania	OMX Vilnius	30	5
Montenegro	MONEX	30	3.8

North Macedonia	MB10	10	4.2
Poland	WIG20	20	357
Romania	BET	10	65.9
Russia	MOEX	43	63
Serbia	BELEX15	15	3.9
Slovakia	SAX	7	2.2
Slovenia	SBITOP	11	10.2
Ukraine	PFTS	20	140*

Note: *in February 2022 when this market closed
Source: ceicdata.com

We can see that the sizes of the markets are very diverse, with the largest capitalizations (Poland and Ukraine) representing more than 50 times those of the smallest markets (Baltic countries and North Macedonia). Likewise, the number of companies included in the indices varies from one country to another, and partly reflects sectoral diversification. It should be noted that trading in the Kyiv stock exchange has been suspended since 24 February 2022, the date when the war began. To conduct an accurate comparison of the three crises, we use an observation window of two years post the event, namely: from 09/30/2008 to 09/30/2010 for the subprime financial crisis in 2008; from 03/02/2020 to 02/01/2022 for the 2020 Covid-19 crisis; and from 02/02/2022 to 02/02/2024 for the start of the war in Ukraine. To enable all markets to be considered, the window for the overall period of analysis extends from 01/08/2006 to 07/06/2024. The daily data were collected on stock exchange websites, and each stock market is represented by its flagship index.
Initially, we estimated several ARMA(p,q) models on the return series (table ii). The optimal lag orders were determined based on information criteria, specifically the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), and the models were fitted accordingly.
The estimated coefficients of the autoregressive (AR) and moving average (MA) components were found to be statistically insignificant. Consequently, the forecasted returns rapidly converged to zero, even over a 90-day horizon. This finding suggests the absence of meaningful short-term autocorrelation or predictable dynamics in the mean of returns.
During both the subprime crisis of 2008 and the COVID-19 crisis of 2020, eight of the sixteen Central and Eastern European countries under study—namely Bulgaria, Croatia, Estonia, Lithuania, North Macedonia, Montenegro, Poland, and Slovakia—exhibited non-significant AR and MA coefficients. In these instances, return forecasts at both 10- and 90-day horizons were close to zero, and the conditional mean displayed no meaningful dynamics. In other words, returns were not predictable (AR), immediate shocks were not persistently reflected in the time series (MA), and no mean-reverting behavior was observable over either the short (10-day) or medium (90-day) term.

In contrast, for Hungary, Latvia, Slovenia, Czechia, and Ukraine, during both the subprime and COVID-19 crises, the AR coefficients were statistically significant and exhibited relatively high values. This suggests that past returns significantly influence current returns. Such results may reflect either market inertia behavior or the presence of mean-reverting dynamics over both short (10-day) and medium-term (90-day) horizons. Furthermore, the absolute value of the MA coefficient was significant in these cases, which may indicate an almost complete compensation of past innovations. Similar patterns were observed for Russia, Serbia, Slovakia, Slovenia, Poland, and Bosnia, particularly during the Ukrainian crisis period.

Table ii. ARMA(p, q) model of short term returns

Country	2008 crisis		Covid crisis		Ukraine war	
	AR	MA	AR	MA	AR	MA
Bosnia	0.105	0.130	0.923***	-0.905***	-0.991***	0.996***
Bulgaria	0.273	-0.074	-0.435	0.473	-0.414	0.520
Croatia	-0.593	0.563	0.542	-0.579	-0.658	0.708
Czech rep.	0.907***	-1.000***	-0.963***	1.000***	-0.066	0.138
Estonia	0.255	-0.139	-0.0159	-0.137	0.009	0.173
Hongary	0.647**	-0.579*	0.961***	-1.000***	-0.429	0.333
Latvia	-0.715***	0.6166**	1.000***	-0.952***	-0.226	0.151
Lithuania	-0.579	0.684*	0.134	-0.064	-0.057	0.005
Montenegro	0.440	-0.258	0.684	-0.956	-0.991	0.965
North Macedonia	-0.085	0.201	0.764	-0.752	-0.341	0.050
Poland	-0.251	0.134	-0.039	0.132	-0.774***	0.671***
Romania	-0.649*	0.729**	0.281	-0.245	-0.081	0.195
Russia	0.866***	-0.841***	0.449	-0.512	-0.822***	0.723**
Serbia	-0.915***	0.883***	0.329	-0.654***	-0.997***	0.999***
Slovakia	-0.095	-0.077	0.711	-0.675	-0.969***	0.998***
Slovenia	0.874***	-1.000***	-0.679***	0.778***	0977***	-1.000***
Ukraine	0.954***	-0.915***	0.870***	-1.000***	-	-

***significant at the 1% error level

Secondly, to assess the presence of long memory, we estimated an ARFIMA(p,d,q) model. The long memory parameter d was estimated to be zero for all countries under consideration, suggesting that the return series does not exhibit long-range dependence and behaves as a short-memory process. This result is consistent with the weak-form Efficient Market Hypothesis, whereby past returns contain no predictive power for future returns.

3.2. Detection of reversion to the mean over a very short period

First, to detect a reversion to the mean in the very short term, we count the number of bullish and bearish trading sessions during the crisis periods on a daily basis. If the upward (UU – increase followed by an increase the next day) or downward (DD – decrease followed by a decrease the next day) trend persists, there is no mean reversion in the short term. However, if an increase is followed by a decrease (UD) or a decrease is followed by an increase (DU), there is a short-term mean reversion from one trading session to the next (Table iii).

Table iii. Possible configurations of a very short-term mean reversion (daily basis)

Market variations	Up in t+1	Down in t+1
Up in t	UU = No mean reversion	UD = Mean reversion
Down in t	DU = Mean reversion	DD = No mean reversion

To measure the frequency of each configuration, we calculate the proportions of each one for each period tested. We thus have:

- Mean reversion in the very short term after an initial increase = UD / (UD + UU)
- Mean reversion in the very short term after an initial decline = DU / (DU + DD)
- Overall mean reversion trend over the period = UD / (UD + UU) + DU / (DU + DD)
- Very short-term momentum effect after an initial increase = UU / (UD + UU)
- Very short-term momentum effect after an initial decline = DD / (DU + DD)
- Overall momentum effect over the period = UU / (UD + UU) + DD / (DU + DD)

3.3. Analysis of the mean reversion in the short and medium terms

Next, we distinguish between the possible mean reversion in the short and medium terms. The index return is measured by:

$$r_{i,t} = \ln(P_{i,t} / P_{i,t-1}) \quad (1)$$

where $P_{i,t}$ is the index price of country i at date t.
We then normalize the returns with:

$$R_{i,t} = r_{i,t} / \sigma_i \quad (2)$$

where σ_i is the standard-deviation of returns over the whole period.

Following Schmidhuber's (2021) method, we then compare the observed returns with the returns which are estimated by a weighted average of past returns. To overweight recent price variations, the chosen weighting is based on an exponential smoothing, i.e.:

$$\widetilde{w}_{T(n)} = M_T e^{-2n/T} \quad (3)$$

where T is the memory length of the estimated return and n is the day of calculation (with 0 as starting point of the whole period). T enables the time lags to be included in the estimated returns. In equation (3) the normalization factor is:

$$M_T = \sqrt{1 - e^{-4/T}} \quad (4)$$

It is rational to consider that investors are more able to determine the consequences of a financial shock and how to remedy them as time passes, and that the impact of this shock can dissipate once it is absorbed by the market. Furthermore, as investors are not exempt from availability bias (Kahnemann 2012), this can lead them to favour the most recent information. The relative weight of each past profitability in the estimated profitability at a given date is then normalized so that the sum of the relative weights reaches 1:

$$\sum_{n=1}^{T} \widehat{w}_{T(n)} = 1 \quad (5)$$

Unlike Schmidhuber (2021), our method does not involve testing lags that range from two days to four years, as these would exceed our post-event windows. Instead, we opt for a short lag and a medium term. Thus, the short memory that we retain corresponds to ten trading sessions, or two weeks, and the medium-term memory corresponds to 90 trading sessions, or slightly more than four months. In the former case, we detect the existence of quasi-immediate memory or short-term post-event mean reversion, and in the latter, we observe persistence or medium-term mean reversion after the initial shock. We then use the model to compare the differences between the observed return and estimated return by calculating their averages over the period studied:

$$E(\Delta_T) = E(\hat{r}_{i,t} - r_{i,t}) \quad (6)$$

for a ten-day and 90-day horizon (T):

$$E(\Delta_{90}) - E(\Delta_{10}) \quad (7)$$

If this difference is positive, this means that $E(\Delta_{10})$ is lower than $E(\Delta_{90})$. We therefore get a better estimate of real profitability if we use a ten-day memory, which shows that there is a mean reversion in the short term. If this difference is negative, the mean reversion takes place over a longer period (90 days).

3.4. Autocorrelation test

Finally, we apply the Ljung-Box test (1978) to determine the serial dependence of returns without weighting past returns. We therefore consider that any possible memory, or momentum, in the return series has the same probability when based on the most recent returns or on the

oldest returns. The H_0 hypothesis of this test is that the data is distributed independently. In other words, the correlations between the returns tend towards 0 and the correlations that are different to 0 are random.
The test statistic is as follows:

$$Q = n(n+2)\sum_{k=1}^{h}\frac{\hat{\rho}_k^2}{n-k} \quad (8)$$

where n is the number of observations, $\hat{\rho}_k$ is the autocorrelation with k lags, and h is the number of tested lags.

Under the H_0 hypothesis, the Q statistic follows a chi-squared distribution $\chi^2(h)$. At an error level α, the critical value to reject the H_0 hypothesis is:

$$Q > \chi^2_{1-\alpha,\, h}$$

where $\chi^2_{1-\alpha,\, h}$ is the $(1-\alpha)$ quantile of the chi-squared distribution with h degrees of freedom.

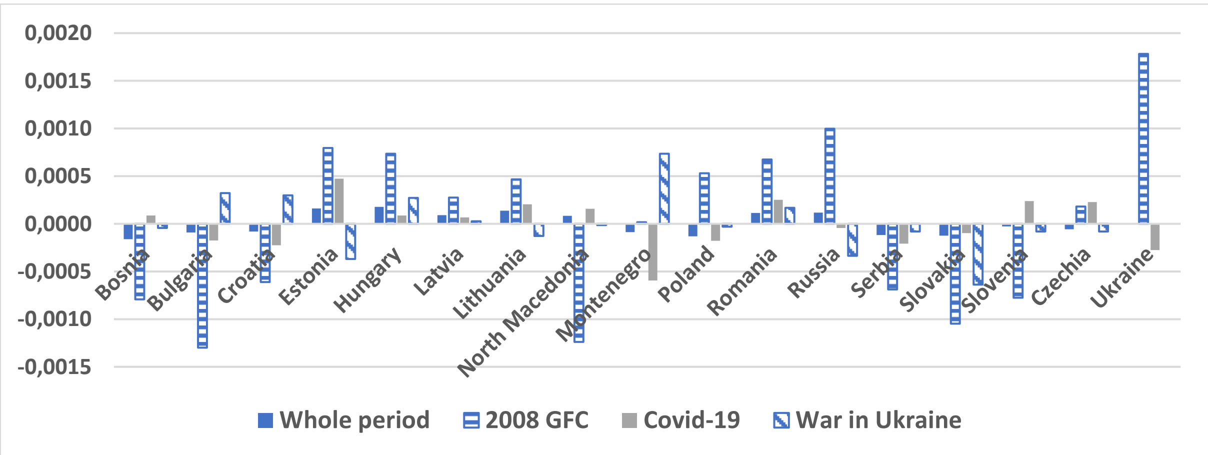
In order to detect the spillovers between markets we also applied the Granger causality test (Granger, 1969). It tests whether past values of one time series variable have significant predictive power for another time series variable. Granger causality does not necessarily imply true causality in the sense of a cause-and-effect relationship, but rather a predictive causality based on temporal precedence.
The null hypothesis H_0 is that the coefficients of the lagged X values in the unrestricted model are jointly equal to zero, meaning X does not Granger-cause Y.
The alternative hypothesis H_1 is that at least one of the lagged X values has a non-zero coefficient, indicating that X Granger-causes Y.
The test uses an F-test to compare the explanatory power of the unrestricted model against the restricted model (meaning that lagged Y values are the only predictors of Y).
If the F-test statistic is significant (i.e., the p-value is below a chosen significance level), we reject the null hypothesis and conclude that X Granger-causes Y. An important consideration in the Granger causality test is the selection of the lag length. Common methods for selecting the lag length include information criteria such as the Akaike Information Criterion (AIC) or the Bayesian Information Criterion (BIC).

4. Results

4.1. Differences between each country and the CEEC average

First, we observe the differences between the average daily returns of the indices of each country and the average returns of all CEECs (Figure 1).

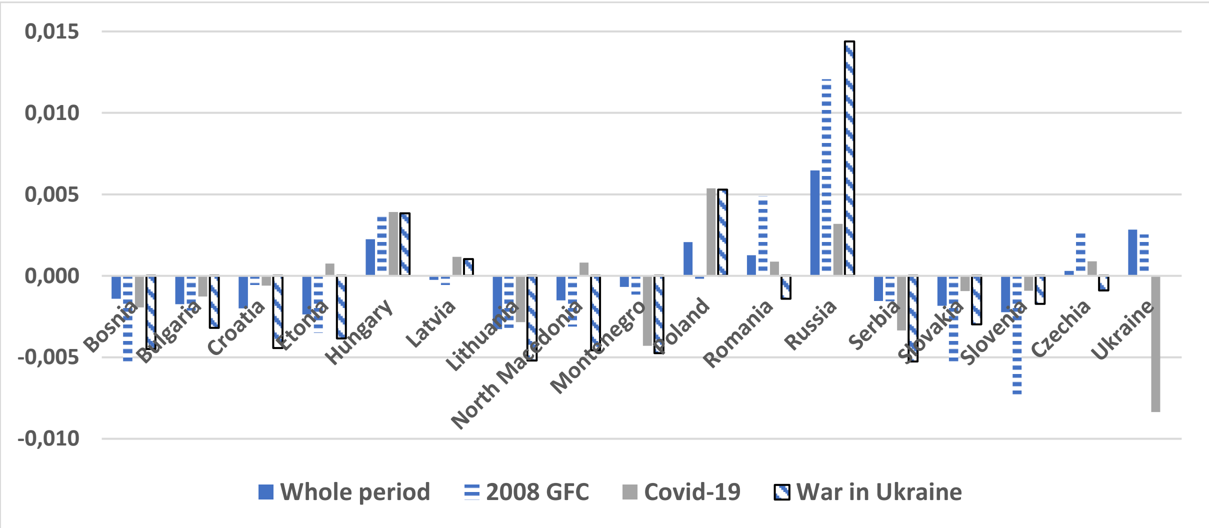
Figure 1. Differences between country returns and the CEEC average returns



Over the whole period (2006-2024), the average daily index returns of each country deviate from the CEEC average, while the situation differs depending on the crisis under consideration. Indeed, the 2008 crisis caused greater losses on the Bulgarian, Macedonian and Slovak markets than on the Russian and Ukrainian markets. The Covid-19 crisis created few differences in the profitability of the CEECs, while the first two years of the war in Ukraine had a larger negative impact on the Slovak, Russian and Estonian markets. The closure of the Kyiv stock exchange since February 2022 means that we are unable to measure the devastating impact on Ukraine.

Figure 2 presents the differences between the standard deviations of the index returns of each country and the average standard deviations of all CEECs. This enables us to add a risk dimension to the profitability results above. When it comes to the volatility of the indices over the whole period, only Russia displays significantly higher volatility than the CEEC average. During the 2008 crisis, Bosnia, Slovakia and Slovenia had lower volatility than the CEEC average, unlike Russia. The differences narrowed during the Covid-19 crisis, whereas volatility increased compared to the average during the first two years of the war in Ukraine for the Hungarian, Polish, Latvian and, especially, the Russian markets. Here again, due to a lack of existing data, we cannot quantify this effect on Ukraine.

Figure 2. Differences between the standard deviation of country returns and the CEEC average standard deviation of returns



It is now appropriate to study the extent to which these contrasting situations were accompanied by a mean reversion effect.

4.2. Mean reversion analysis in the very short term

We can see that there is no clear mean reversion trend for the large markets of Poland, Czechia and Hungary, but there are some opportunities for investors who wish to take advantage of short trends in small markets (Table iv). Thus, the momentum effect is observed both in the short and longer term over the entire period in Bosnia, North Macedonia, Montenegro, Romania and Ukraine and has been detected since the beginning of the Ukraine war in Bosnia, Hungary, North Macedonia, Romania and Slovakia (Table v).

Table iv. Mean reversion in very short-term returns (daily basis)

Country	After an initial increase UD/(UD+UU)			After an initial decrease DU/(DU+DD)		
	2008 crisis	Covid crisis	Ukraine war	2008 crisis	Covid crisis	Ukraine war
Bosnia	38.08	58.21	51.80	48.42	38.61	40.28
Bulgaria	42.57	55.17	56.05	44.40	49.23	46.32
Croatia	48.37	57.01	54.15	45.95	45.16	45.93
Czech rep.	50.20	53.33	49.58	47.66	43.48	43.66
Estonia	47.37	47.17	45.00	46.03	34.60	47.37
Hungary	53.28	52.74	48.68	49.81	46.99	40.74
Latvia	56.46	52.82	59.83	54.51	53.25	55.00
Lithuania	46.31	56.16	50.22	44.98	43.93	43.49
Montenegro	41.22	55.88	65.88	45.73	38.98	34.37
North Macedonia	33.75	47.32	42.34	40.72	33.80	42.86
Poland	50.99	51.00	51.78	50.79	49.61	52.19
Romania	50.66	51.75	51.63	42.77	42.24	38.54
Russia	56.43	56.19	50.45	52.33	44.84	42.86
Serbia	35.93	53.25	52.10	40.68	50.97	46.95
Slovakia	67.10	73.33	80.47	29.94	32.16	27.84
Slovenia	41.73	59.80	48.75	42.23	38.56	45.17
Ukraine	46.19	89.13	-	38.29	9.07	-

Table v. Momentum effect in very short-term returns (daily basis)

Country	After an initial increase UU/(UD+UU)			After an initial decrease DD/(DU+DD)		
	2008 crisis	Covid crisis	Ukraine war	2008 crisis	Covid crisis	Ukraine war
Bosnia	51.58	61.39	59.72	61.92	41.79	48.20
Bulgaria	55.60	50.77	53.68	57.43	44.83	43.95
Croatia	54.05	54.84	54.07	51.63	42.99	45.85
Czech rep.	52.34	56.52	56.34	49.80	46.67	50.42
Estonia	53.97	65.40	52.63	52.63	52.83	55.00
Hungary	50.19	53.01	59.26	46.72	47.26	51.32
Latvia	45.49	46.75	45.00	43.54	47.18	40.17
Lithuania	55.02	56.07	56.51	53.69	43.84	49.78
Montenegro	54.27	61.02	65.63	58.78	44.12	34.12
North Macedonia	59.28	66.20	57.14	66.25	52.68	57.66
Poland	49.21	50.39	47.81	49.01	49.00	48.22
Romania	57.23	57.76	61.46	49.34	48.25	48.37
Russia	47.67	55.16	57.14	43.57	43.81	49.55
Serbia	59.32	49.03	53.05	64.07	46.75	47.90
Slovakia	70.06	67.84	72.16	32.90	26.67	19.53
Slovenia	57.77	61.44	54.83	58.27	40.20	51.25
Ukraine	61.71	90.93	-	53.81	10.87	-

Overall, there appears to be very little mean reversion over the three periods tested. The crisis with the clearest mean reversion is the Covid-19 crisis, undoubtedly because of the fairly quick return to a usual global economic situation in contrast to the persistence of the other two crises several months after they were triggered. We also checked whether the lockdown dates during the Covid-19 crisis correspond to specific values for very short-term memory. The lockdown or state of emergency periods were approximately the same for all countries, ranging from mid-March 2020 to mid-April (Hungary and Ukraine), mid-May (Bosnia, Estonia, Montenegro, Romania and Russia) and early June 2020 for the others. No relationship was observed between the lockdown periods and the importance of mean reversion in the very short term.

4.3. Mean reversion analysis in the short and medium terms

The $E(\Delta_{90}) - E(\Delta_{10})$ difference indicates the extent to which the difference between the average of the exponentially weighted returns over the 90 days preceding time t and the observed return at time t is greater than the spread between the exponentially weighted average over the ten days preceding time t and the observed return at time t. In other words, $E(\Delta_{90}) < E(\Delta_{10})$ indicates that the medium-term memory is more precise than the short-term memory and, therefore, that there is a mean reversion in the medium term (here 90 days). Similarly, $(\Delta_{90}) > E(\Delta_{10})$ shows that the short-term memory is more precise than the medium-term memory and, therefore, that there is a mean reversion in the short term (here ten days).

The results in Table vi show that each crisis has had notable impacts on returns, with clearer mean reversion in the medium term than in the short term for all the CEECs during the 2008 crisis. A similar pattern is observed during the conflict in Ukraine, with the exception of Serbia, indicating that this particular event did not alter the medium-term mean reversion dynamics. However, the observations regarding the COVID-19 crisis present a more nuanced picture. Specifically, nine out of the seventeen financial markets (highlighted in bold) exhibited greater mean reversion in the short term compared to the medium term, as evidenced by positive values of $\overline{E(\Delta_{90}) < E(\Delta_{10})}$. This suggests that the health crisis was unique in its impact, effectively shortening the mean reversion horizon.

Table vi. Accuracy of short-term memory in CEECs during crises in terms of the return average

	$E(\Delta_{90}) - E(\Delta_{10})$		
Return average	**2008 crisis**	**Covid crisis**	**Ukraine war**
Bosnia	-0.00041663	-0.00004821	-0.00003520
Bulgaria	-0.00032782	**0.00005256**	-0.00006377
Croatia	-0.00023340	-0.00002856	-0.00004427
Czech rep.	-0.00015298	-0.00002229	-0.00003586
Estonia	-0.00026347	**0.00010887**	-0.00002955
Hungary	-0.00015691	-0.00004503	-0.00008741
Latvia	-0.00033485	**0.00002210**	-0.00003671
Lithuania	-0.00041248	**0.00006801**	-0.00005326
Montenegro	-0.00022016	**0.00005357**	-0.00005892
North Macedonia	-0.00004468	**0.00007455**	-0.00005605
Poland	-0.00019111	-0.00000007	-0.00009689
Romania	-0.00041244	-0.00001084	-0.00000151
Russia	-0.00045496	**0.00018793**	-0.00017168
Serbia	-0.00043064	-0.00001063	**0.00006026**
Slovakia	-0.00002690	**0.00002967**	0.00003480
Slovenia	-0.00022017	**0.00004438**	-0.00005984
Ukraine	-0.00061996	-0.00001399	-

Note also that the precision of the medium-term memory is slightly better during the 2008 crisis ($E(\Delta_{90}) < E(\Delta_{10})$) than for the other two crises, as the values are all negative. Indeed, the variation among differences is higher during the 2008 crisis than the other two crises for almost all CEECs. This may be explained by the deep and lasting economic impact of the 2008 crisis, which was more pronounced than the other two.

With regard to the volatility generated by crises, measured by $E(\Delta_{90}) - E(\Delta_{10})$ calculated on the standard deviations of daily returns, we observe a mean reversion in the short term during the 2008 crisis, while the situation is more heterogeneous during the other crises. Likewise, as shown in Table vii, which gives the results of the calculations of $E(\Delta_{90}) - E(\Delta_{10})$ on the kurtosis of daily returns, the mean reversion (i.e. a return to less excessive extreme values) took place in the medium term for most countries.

Table vii. Accuracy of the short-term memory in CEECs during crises in terms of the return kurtosis

	$\boldsymbol{E(\Delta_{90}) - E(\Delta_{10})}$		
Return kurtosis	**2008 crisis**	**Covid crisis**	**Ukraine war**
Bosnia	7.85667823	6.09554500	11.19408247
Bulgaria	4.83633574	15.56512487	8.21437107
Croatia	3.60562017	19.99502507	6.68049164
Czech rep.	5.06981008	11.50323655	2.15258436
Estonia	1.97024579	14.36128730	5.42292936
Hungary	3.05239096	9.17440192	7.90084327
Latvia	3.04907601	54.85700107	7.62670041
Lithuania	7.63879788	15.77319701	16.91556959
Montenegro	5.59210995	7.12936534	2.77234521
North Macedonia	2.88983390	15.28908983	22.91353490
Poland	1.31919122	11.39153435	2.48417834
Romania	3.24775931	13.16664175	4.41740816
Russia	9.27746039	6.61787569	79.57228592
Serbia	4.14198321	15.30929167	1.20037728
Slovakia	7.66968286	6.50109663	8.45110878
Slovenia	7.30100319	10.77434672	8.29444411
Ukraine	3.98719177	12.71490999	-

We note that the Russian market has been more affected by the war, which is a source of great uncertainty and heterogeneous political positions within the CEECs vis-à-vis Russia. It is important to look at the results of small markets with some caution, because for some of them (Bosnia, Bulgaria, Croatia, Estonia, Latvia, Lithuania, Montenegro, North Macedonia, Slovakia, Slovenia) the number of listed companies and the size of the index does not allow full diversification of securities portfolios for investors.

4.4. Ljung-Box autocorrelation tests

The goodness-of-fit of our time series model is confirmed by the non-significant residual autocorrelations observed at both 1-day and 5-day lags. However, at the 21-day lag, residual autocorrelations were found to be significant at the 5% level exclusively for Poland and Estonia during the period of the Ukraine conflict. This indicates that the residuals predominantly exhibit characteristics of white noise in the short term. Consequently, this finding reinforces our

decision to consider the medium term as potentially significant for identifying mean reversion effects.
The results of the Ljung-Box tests, shown in Table viii, were calculated with one, five and 21-day lags. For all countries, the figures indicate the presence of positive, but not significant, autocorrelation. We can conclude that there is no momentum effect and no significant mean reversion effect. This therefore confirms our previous results. Furthermore, there is no specificity in terms of the type of crisis or the country considered.

Table viii. Ljung-Box autocorrelation tests on CEEC markets

Country	Whole period (2007-2024)			2008 crisis (2007-2009)			Covid crisis (2020-2022)			Ukraine war (2022-2024)		
Lags: 1, 5 or 21 days	LB(1)	LB(5)	LB(21)	LB(1)	LB(5)	LB(21)	LB(1)	LB(5)	LB(21)	LB(1)	LB(5)	LB(21)
Bosnia (SASX10)	1.237	11.280	22.890	0.553	2.984	14.917	0.417	3.667	30.468*	0.024	1.343	25.989*
Bulgaria (SOFIX)	0.142	6.882	29.709*	0.248	4.253	23.862*	0.404	3.064	8.842	0.174	1.767	14.376
Croatia (CROBEX)	1.924	7.165	19.544	0.759	8.855	33.834*	0.404	1.464	23.812	0.491	5.720	17.618
Czech rep. (PX)	0.293	3.958	15.136	0.149	4.757	11.821	0.321	3.211	24.235	0.782	4.591	19.215
Estonia (OMX Tallinn)	0.834	5.170	15.698	0.499	3.382	12.953	0.525	1.379	23.895	2.003	9.271	35.031**
Hungary (BUX)	0.665	8.340	20.895	2.040	7.921	20.433	0.436	11.607	21.836	0.208	4.010	24.804
Latvia (OMX Riga)	1.060	4.978	28.506*	0.581	5.406	27.061*	0.043	2.741	15.176	0.516	1.808	14.167
Lithuania (OMX Vilnius)	0.140	8.090	24.673	0.075	5.098	16.077	0.049	4.805	13.018	0.822	4.144	13.227
Montenegro (MONEX)	0.077	7.338	25.587*	0.068	1.881	16.344	0.454	4.887	22.084	0.065	8.998	27.847*
North Macedonia (MB10)	0.062	6.820	21.855	0.043	4.563	12.361	0.007	3.952	16.108	0.262	3.419	20.987
Poland (WIG20)	1.769	1.783	16.781	0.297	2.351	10.810	0.001	0.059	14.191	0.077	5.239	30.269**
Romania (BET)	0.069	7.523	20.415	0.287	3.222	18.079	0.651	3.428	26.619	0.877	3.027	24.515
Russia (MOEX)	0.532	4.750	27.663*	0.048	2.857	17.404	0.134	7.772	19.647	0.529	2.294	11.175
Serbia (BELEX15)	0.699	8.450	24.622	0.147	0.623	22.861	0.011	6.244	16.482	0.979	5.921	21.831
Slovakia (SAX)	0.268	7.026	25.725	0.321	1.394	18.277	0.027	0.151	22.284	0.376	8.765	18.241
Slovenia (SBITOP)	1.207	8.771	16.414	0.253	8.052	20.962	0.744	5.054	13.511	0.319	7.827	25.663*
Ukraine (PFTS)	0.756	5.172	18.246	0.157	2.199	15.397	0.532	7.451	27.591	-	-	-

*significant at the 10% error level, ** significant at the 5% level

4.5.VAR model and Granger causality tests

To assess the existence of potential spillover effects between countries, we estimated a Vector Autoregression (VAR) model using the daily return series of the relevant financial markets. We

selected the optimal lag structure using the AIC criterion and performed Granger causality tests to identify the direction and significance of spillovers.
To enhance the interpretability of spillover effects within our VAR models, we adopted a grouping strategy based on a set of clear and economically relevant criteria. Given the heterogeneity of the countries in our sample—which includes Central and Eastern European markets as well as Russia—we formed subgroups of four countries to construct parsimonious and tractable VAR models. The grouping was primarily guided by two criteria: geographical proximity and the degree of European integration, whether through EU membership, euro adoption, or financial convergence. The table ix below summarizes the four groups, the countries included in each, and the main rationale for their classification.

Table ix. Four groups of countries

Group	**Proposed Label**	**Included Countries**	**Main Justification**
G1	Western Balkans	Bosnia, North Macedonia, Montenegro, Serbia	Coherent geographical region, non-EU members, similar level of integration
G2	South-Eastern Europe	Bulgaria, Romania, Croatia, Slovenia	EU or Eurozone members, increasing financial integration
G3	Baltic Countries	Estonia, Latvia, Lithuania, Poland	Northeastern region, strong EU dependence, euro area membership or close alignment
G4	Central Europe + Russia	Czech Republic, Slovakia, Hungary, Russia	Historical core of Central Europe, strong geopolitical influence

For each of the four country groups, we also estimated a distinct VAR model and performed Granger causality tests to identify the direction of transmission across markets and to evaluate the regional dynamics and to conduct a visual comparison of spillover effects across Central and Eastern European financial markets. Ukraine was not included in any of the groups, as stock market quotations were suspended in February 2022. This interruption rendered it impossible to conduct Granger causality tests or to assess potential spillover effects involving the Ukrainian market. Considering the results in tables x to xiii, within each group, there is evidence of Granger causality (significant F-statistic) from one country to the others in each group.

Table x : Granger Causality Test and Instantaneous Causality Test on Group 1

Group 1	Influenced countries	2008 crisis		Covid crisis		Ukraine war	
Cause		F-stat.	Chi²	F-stat.	Chi²	F-stat.	Chi²
North Macedonia (MdN)	M, S, B	4.7635***	3.7481	4.7519***	41.646***	0.53304	4.2208
Montenegro (M)	MdN, S, B	2.9861***	25.469***	1.3342	3.2783	3.724**	5.4613
Serbia (S)	MdN, M, B	3.2161***	30.312***	2.836***	40.192***	0.28332	9.5674**
Bosnia (B)	MdN, M S	2.0316**	10.027**	1.0895	5.4763	2.0039	9.1659**

***significant at the 1% error level, ** significant at the 5% error level, * at the 10% error level

Table xi : Granger Causality Test and Instantaneous Causality Test on Group 2

Group 2	Influenced	2008 crisis		Covid crisis		Ukraine war	
Cause	countries	F-stat.	Chi²	F-stat.	Chi²	F-stat.	Chi²
Bulgaria (B)	R, C, S	2.2687*	49.634***	9.6651***	3.8524	3.5381***	14.847***
Romania (R)	B, C, S	0.11	127.51***	2.6414***	5.6029	2.6084***	5.6847
Croatia (C)	B, R, S	21.406***	132.41***	7.2607***	59.445***	6.8965***	10.036**
Slovenia (S)	B, R, C	2.9635**	100.38***	3.2069***	58.103***	1.1868	1.0327

Table xii : Granger Causality Test and Instantaneous Causality Test on Group 3

Group 3	Influenced	2008 crisis		Covid crisis		Ukraine war	
Cause	countries	F-stat.	Chi²	F-stat.	Chi²	F-stat.	Chi²
Poland (P)	La, E, Li	3,2642**	5,0105	4.9005***	27.915***	1.1931	1.6182
Latvia (La)	P, E, Li	2,0939	10,445**	5.7123***	15.561***	1.7466***	2.6049
Estonia (E)	P, La, Li	2,0799	2,2419	3.6673***	95.598***	1.5151**	3.4286
Lithuania (Li)	P, La, E	3,1516**	8,0841**	18.867***	102.33***	7.8916***	2.0412

Table xiii : Granger Causality Test and Instantaneous Causality Test on Group 4

Group 4	Influenced	2008 crisis		Covid crisis		Ukraine war	
Cause	countries	F-stat.	Chi²	F-stat.	Chi²	F-stat.	Chi²
Slovakia (S)	CR, H, R	1.7157**	1.4944	1.2525	0.0898	1.1995	3.901
Czech Rep. (CR)	S, H, R	2.9715***	67.646***	3.145***	94.381***	5.889***	12.673***
Hungary (H)	CR, S, R	3.4919***	48.456***	1.9888***	92.574***	9.8644***	43.169***
Russia (R)	CR, S, H	3.4919***	48.456***	6.0044***	13.497***	2.0587**	48.754***

Exceptions to this finding include Slovakia in Group 4 across all crises, Poland in Group 3, and North Macedonia in Group 1 during the Ukraine crisis. Additionally, instantaneous causality within each group, which implies strong interdependence or synchronization of financial markets, is also present (significant Chi2), except during the Ukraine crisis for Group 3. The values are particularly high and significant in Group 4 across the three crises, with the exception of Slovakia.

In conclusion, the Granger causality tests applied to a multivariate VAR model reveal significant dynamic interactions among the financial markets of the countries studied. This finding is consistent with a crisis context in which markets collectively respond to the same shocks. More specifically, the results indicate that the markets of most Central and Eastern European Countries (CEECs) exert a predictive influence on the markets of other countries within each group (significant F-tests). Furthermore, tests for instantaneous causality highlight significant contemporary interdependence among these countries, suggesting a high degree of market synchronization. These results support the hypothesis of regional spillover effects, underscoring the importance of cross-border transmission of financial shocks in the region.

5.Conclusion

While there have been several studies on mean reversion, there has been no comparative analysis of the effects of different crises on the CEECs. This study therefore fills this gap by observing the stock markets of all CEECs during the three most recent crises. Several interesting results can be highlighted. First, there is no significant mean reversion effect in the very short term (daily variations) but there has been a momentum effect in five markets since the beginning of the war in Ukraine. Second, the originality of the exponential weighting used in the calculations of deviations on moving averages enabled us to show a more pronounced mean reversion effect in the medium term (90 days) than in the short term (ten days) during the 2008 financial crisis as well as since the start of the war. Third, in contrast, during the Covid-19 crisis the mean reversion effect was more noticeable in the short term than in the medium term. Fourth, when considering the volatility of the indices, we noticed a clearer return to the mean in the short term, particularly during the 2008 crisis. Fifth, the Russian stock market was affected more by the period at the start of the war in Ukraine, with a kurtosis of the differences in daily returns much higher than in the other CEECs. Our results can help to build better investment strategies in CEEC stock markets and to optimize portfolio diversification. Sixth, Granger causality tests within a multivariate VAR model show significant interactions among financial markets. Instantaneous causality tests reveal strong interdependence and synchronization, supporting regional spillover effects and highlighting the importance of cross-border financial shock transmission.

This empirical study, which is exhaustive in its consideration of the CEEC stock markets, is not comprehensive in terms of type of crisis. To a credit crisis (subprimes), a health crisis (Covid-19) and a geopolitical crisis (war in Ukraine), we would have liked to add the case of a speculative bubble (internet bubble in 2000) or a bond crisis. We were unable to do this because of the recent (re)opening of some financial markets in the CEECs and this therefore constitutes a limitation of this research. In addition, it was not possible to analyse stocks or sectors due to the small size and lack of diversification of several markets. This work could be extended by simulating investment portfolios in the CEECs and adjusting the purchases and sales of the various indices according to the speed of the mean reversion in order to extract positive abnormal returns. This would demonstrate the applicability of these results as part of an investment strategy.

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