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Time-dependent complexity measurement of causality in international equity markets: A spatial approach

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ABSTRACT

A nonlinear temporal complexity approach is proposed in order to properly model the evolution of randomness, self-similarity and information transmission for thirty-four international stock markets, grouped into four major geographical segments: America, Europe, Asia and Oceania. The causality between each type of time-dependent measures is investigated to assess the state system flows across all geographic segments. The empirical results show that self-similarity is vastly transmitted between financial markets. Moreover, significant emissions of entropy and self-similarity are found between America and Europe. Informational flows are observed only between Europe and Asia, and Europe and Oceania. Our findings may have important implications for portfolio management based on the spatial dimension of spillovers of stochasticity, self-similarity and system state informational content for world stock markets. These results would not have emerged by means of standard econometric approaches of causality investigation in financial returns.

1. Introduction

Nonlinear analysis of financial time series is an expedient way to extract the hidden patterns of their inherent dynamics. Common measures from nonlinear analysis are entropy, self-similarity and information content measures. They are drawn from information theory and statistical physics, and are appropriate for the analysis particularly of non-stationary signals. In recent years, there has been a renewed interest in analyzing stock markets by means of these complexity measures. For instance, entropy investigation from thirty international financial markets revealed that the degree of randomness has increased in the aftermath of the recent world global financial crisis [1], whilst in commodity markets significantly varied across pre-crisis, and post-crisis time periods [2]. Additionally, the analysis of entropy in Bitcoin markets demonstrated that considerably increased during times of high-level in prices [3]. In other works, entropy was employed to assess the predictability of aggregate market fears in 1987 and 2008 [e.g., 4]. It was concluded that entropic indicators are more effective than common stock market sentiment ones. When employed to characterize returns from family business companies and Casablanca stock market returns [5], it was found that their respective entropy functions are characterized by nonlinear dynamics. In another interesting work, entropy was employed towards the determination of the optimal level of multi-resolution decomposition with applications to exchange markets during the global financial crisis and the Eurozone debt crisis [6]. The approach was interestingly found to be able to reveal new stylized properties. Furthermore, in conjunction with entropy it was effectively employed in the context of financial networks whereby it was found that accurately captured the structural differences in graph-based theory networks [7]. More recently, the empirical findings in [8] indicated that entropy in return and volatility series of fertilizer markets increase significantly during time periods of high variability.

Moreover, self-similarity measurement was employed in various studies [9,10]. For instance, it was concluded that Portuguese stock market returns are highly unpredictable, considerably higher than the efficient market hypothesis assumes and normally distributed return series, and has no long memory traits [9]. Persistence in the Ukrainian stock market during the recent financial crisis was examined in [10] and empirical findings showed that the market is inefficient and the degree of persistence is not the same at different stages of the financial crisis. In [11], a study of long-range dependence in portfolio factors revealed that for the period from 1931 to 2014 (US stock market) and from 1990 to 2014 (twenty international stock markets), no systematic evidence of persistence or anti-persistence in the factor returns was indicated. The authors in [12] examined the independence assumption for the US stock

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market indices and individual firms. They concluded that the tails of the probability distributions are too fat, large changes in magnitude are too frequent, and data-generating processes have embedded memory features. Lastly, it was found that self-similarity and signal processing techniques can reveal information contained in different amplitudes of the Chinese stock markets returns [13].

Other measures of information theory were successfully employed in various econophysics studies, for instance modeling dynamics of stock markets [14], ranking of stock exchanges and individual company stocks in terms of their relative efficiency [15,16] and investigating the complicated relationship between predictability of price changes and the profitability of algorithmic trading [17]. In addition, information theory measures were applied to study the nonlinear complex evolution of financial dynamics in a random visibility graph framework [18], to develop a random agent-based financial price dynamics model [19], to investigate the characteristics of extreme events in financial markets [20], and to study nonlinear complexity of volatility duration and volatility difference component of stock prices within a voter interacting system [21].

Motivated by the fact that entropy, self-similarity, and information content are suitable measures to characterize the inherent nonlinear dynamics of stationary and non-stationary series in financial markets based on their ability to respectively quantify randomness, long-range memory, and order/disorder, we seek in this present study to evaluate their respective time-dependent fluctuations in a large set of international stock markets grouped by geographical segments. Consequently, our main purpose is to assess the causal effects between each type of time-dependent complexity measures across various geographic segments. Indeed, assessing those causal effects can effectively shed light on external sources of nonlinearities and system perturbation. Particularly, we can obtain useful information on how transmission of entropy, self-similarity and information content flows occurs between stock markets, under specific by geographic segments.

There are numerous works in econophysics literature where two interesting issues are separately examined: complexity measures in market data and causal effects between price returns. However to our knowledge, this study is the first to combine entropy, self-similarity, information content and causality in a single framework, whereby causality in each type of those complexity measures is scrutinized. In fact, we extend the standard approach on investigation relationships between stock markets which is essentially based on causality of returns, by considering a novel perspective based on causality in time-dependent nonlinear patterns represented by time-varying complexity measures. In this regard, our results can improve the understanding of complexity transmission between various geographic equity markets. Consequently, the problem of possible portfolio diversification is alternatively addressed within the transmission framework of nonlinear patterns between global stock markets.

Our contributions are summarized as follows: firstly, we rely on time-dependent complexity measures captured by entropy, self-similarity and information theory to study the evolution of randomness, long-range memory and information flows in major stock markets with respect to their geographical context. Secondly, we estimate the causal effects between those time-dependent complexity measures. Such estimation allows discovering directional effects; for instance, transmission of randomness, long-range memory and information content between some of the key geographic markets. Thirdly, the statistically significant causal influences are discovered and revealed.

We utilize Shannon entropy (SE) [22] to quantify randomness in prices. In addition, self-similarity in prices is captured by using Detrended fluctuation analysis (DFA) [23]. Furthermore, the Lempel–Ziv complexity (LZC) measure [24] is employed to assess the information content in prices. Finally, causality between time-dependent nonlinear patterns is assessed by the Granger test [25]. In this respect, by checking the significance level, we find which geographical region is the cause of complexity transmission from and to the other regions. Indeed, the Granger causality framework is straightforward and provides robust statistical inference, hence becomes easy to interpret the generated results. We discover the various sources of transmission of randomness, long-range memory, and informational content between all investigated geographical segments.

The rest of the paper is organized as follows: the next section presents the methods employed in our study. Then, data description and results are provided in Section 3. Finally, we conclude in the Section 4 with economic implications.

2. Methodology

2.1. Shannon entropy

Shannon entropy [22] is employed to quantify randomness in nonlinear and non-stationary signals. If we consider the following price time series $X=\{x_i\}_{i=1}^{n}$, then the Shannon entropy (SE) is expressed as:

$$SE(X) = -\sum\nolimits_{i=1}^{n} p(x_i)\,\log p(x_i) \tag{1}$$

where $p(x_i)=\mathrm{Prob}(X=x_i)$ is a discrete probability such that $\sum_i p_i = 1$. Shannon entropy reaches its maximum when all values of the underlying informational price time series $\{x_i\}_{i=1}^{n}$ are equally probable. Particularly, when it comes close to $\log(n)$, $\{x_i\}_{i=1}^{n}$ is nearly random. Conversely, Shannon entropy approaches a minimum score when a particular x_i is guaranteed to happen, for instance with $p(x_i)=1$. In this study, a rolling (sliding) window of 300 observations is used to consistently and dynamically compute time-dependent Shannon entropy from the price time series.

2.2. Detrended fluctuation analysis

The Detrended fluctuation analysis (DFA) [23] is suitable to measure self-similarity and describe intrinsic nonlinear dynamics in signal processing. For a given signal x, the computational steps of the DFA are described as follows:

a) Define the suite y_N of the cumulative series of original signal x_i fluctuations about its mean:

$$y_N = \sum_{i=1}^{N} (x_i - \bar{x}) \tag{2}$$

b) Divide y_N into boxes of equal length n.

c) In each box, we fit the local trend of y_N by a polynomial $P(n,\mathrm{N})$ that corresponds to local trend of the box. We set the polynomial of degree to unity.

d) For the given n box size, we calculate the root-mean-squared Detrended fluctuation of the signal y_N as:

$$F(n,\mathrm{N}) = \sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}} (y_i - P(n,\mathrm{N}))^2} \tag{3}$$

For each of the available n box size, the last step is repeated to get the empirical relationship between the overall fluctuation $F(n,\mathrm{N})$ and the box size n:

$$F(n,\mathrm{N}) \propto n^{\mathrm{H}} \tag{4}$$

Finally, the Hurst exponent HE is estimated by running a regression of $\log(F(n,\mathrm{N}))$ on $\log(n)$. A sliding window of 300 observations is used again to dynamically compute the time-dependent DFA-based Hurst exponent from the price series.