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# Multiscale and cross entropy analysis of auroral and polar cap indices during geomagnetic storms

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**Abstract**

In order to improve general monoscale information entropy methods like permutation and sample entropy in characterizing the irregularity of complex magnetospheric system, it is necessary to extend these entropy metrics to a multiscale paradigm. We propose novel multiscale and cross entropy method for the analysis of magnetospheric proxies such as auroral and polar cap indices during geomagnetic disturbance times. Such modified entropy metrics are certainly advantageous in classifying subsystems such as individual contributions of auroral electrojets and field aligned currents to high latitude magnetic perturbations during magnetic storm and polar substorm periods. We show that the multiscale entropy/cross entropy of geomagnetic indices vary with scale factor. These variations can be attributed to changes in multiscale dynamical complexity of non-equilibrium states present in the magnetospheric system. These types of features arise due to imbalance in injection and dissipation rates of energy with variations in magnetospheric response to solar wind. We also show that the multiscale entropy values of time series decrease during geomagnetic storm times which reveals an increase in temporal correlations as the system gradually shifts to a more orderly state. Such variations in entropy values can be interpreted as the signature of dynamical phase transitions which arise at the periods of geomagnetic storms and substorms that confirms several previously found results regarding emergence of cooperative dynamics, self-organization and non-Markovian nature of magnetosphere during disturbed periods.


*Keywords:* Magnetosphere; Time series analysis; Multiscale permutation entropy; Cross sample entropy

## 1. Introduction

The Earth's magnetosphere is a multiscale spatiotemporal complex dynamical system driven incessantly by solar wind. Self Organized Criticality (SOC) corresponds to the general idea that certain classes of dynamical systems organize themselves to a critical state through active processes having infinite separation of time scales, whose macroscopic behavior exhibit features such as scale invariance, without further tuning of parameters (Bak et al., 1987, 1988). In the magnetosphere, a number of phenomena have been interpreted as characteristics of SOC such as geomagnetic substorms, magnetotail current disruptions, bursty bulk-flow events, and auroras seen in ultraviolet and optical wavelengths (Aschwanden, 2011; Watkins et al., 2015). The most important property of nonlinear systems which evolve into SOC is that they self-organize into a unique global dynamic state with underlying complex dynamics at all spatio-temporal scales. Near SOC, the correlations among the fluctuations are extremely long ranged and there exist many correlation scales. This kind of multiscale behavior seems to occur naturally in complex systems, and is necessary for the existence of an out-of-equilibrium

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globally stable state with underlying multiscale turbulence and instabilities. In recent years, investigations on the complex nature of the magnetosphere introduced various new concepts such as, to list a few, the transitions to high dimensional SOC, appearance of low dimensional chaoticity, presence of multifractal and intermittent structures, which are invariably inherent in the dynamics of complex nonlinear systems (Vassiliadis et al., 1990, 1991; Klimas et al., 1996; Pavlos et al., 1999; Sitnov et al., 2000; Consolini, 2002; Consolini et al., 2008; Pulkkinen et al., 2006).

Geomagnetic storm is an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere–ionosphere system, to an intensified ring current strong enough to exceed a key threshold of the disturbance quantifier, the Dst index (Gonzalez et al., 1994). Magnetic storms make the solar wind-magnetosphere-ionosphere ($SW-M-I$) coupling more complex, which in turn creates several active degrees of freedom with various magnitudes of coupling among them. The spatio-temporal chaotic behavior of the magnetosphere during geomagnetic storms emphasizes the role of internal as well as external processes in the temporal and spatial evolution of the system. Such forces, generated as a result of superposition of turbulence and instabilities, due to strong interactions and mutual deformations of fields developing in plasma sheet, in turn attribute to the characteristic nonlinear fluctuations of the auroral indices. Also, a combination of the geomagnetic storm and polar substorm together manifest certain unique, well-correlated phenomena in the magnetosphere and auroral/sub-auroral ionosphere (Huang et al., 2003).

Auroral electrojet index ($AE$) is based on 1-min values of the H-component trace from auroral-zone observatories located around the world. The upper and lower envelopes are defined as $AU$ and $AL$ indices, respectively, and they represent the maximum eastward and westward electrojet currents. The sum of the absolute values of $AL$ and $AU$ is called $AE$ (Davis and Sugiura, 1966). During magnetically disturbed times the westward electrojet, whose proxy is the $AL$ index, increases abruptly due to currents from the magnetotail. On the other hand, the eastward electrojet, whose proxy is the $AU$ index, increases due to the partial ring current closure via the ionosphere in the evening sector (Feldstein et al., 2006). The Earth's auroras typically form in an oval configuration around the magnetic poles, encircling a dim region called the polar cap. The polar cap index ($PC$) is a measure of the geomagnetic activity at high latitudes where these magnetic perturbations are mostly due to the field-aligned currents flowing at the poleward rim of the auroral oval and to the ionospheric Hall currents in the polar cap. Geomagnetic activity in the polar cap region is due to several phenomena which can be very localized, such as polar cap substorms or those that affect entire polar cap region, such as the poleward shrink of the auroral oval (Troshichev et al., 1988; Vennerstrøm et al., 1991).

Information entropy is a powerful concept in complexity analysis (regarding it identical to thermodynamic entropy) to characterize the diversity of patterns present in geomagnetic indices, but till now, its application to analyze such data has been constrained to a limited number of studies. In order to measure complexity in geophysical data, entropy methods can be used which are based on delay embedding, symbolic dynamics, recurrence plots and multiscale power laws of associated time series. The major advantage of the entropy based approach resides in its ability to account for nonlinear dependences. Entropy based algorithms measure the degree of orderliness of a time series by the occurrence of repetitive patterns. Entropy increases with increase in degree of disorder and reaches a maximum for completely random systems. Based on the fact that the entropy of a time series depends on its standard deviation and correlation properties, uncorrelated stochastic signals with larger variances have higher entropy values, while the entropy of a periodic signal is smaller than that of a random one (Costa et al., 2005). Instead of using conventional approaches for measuring entropy of geophysical systems, which cannot account for the inherent multiple spatiotemporal scales hidden inside, it will be more productive to use the multiscale entropy methods for their analysis. Hence, our approach to define an entropy measurement focuses on quantifying the information expressed by the magnetospheric indices over multiple scales for both univariate and bivariate data (Costa et al., 2002, 2005; Liu et al., 2010; Koutsoyiannis, 2011; Ahmed and Mandic, 2011; Consolini and De Michelis, 2014; Gopinath et al., 2015; Weck et al., 2015).

The auroral electrojet indices provide the detailed dynamical features of the global aspects of auroral substorms. The geomagnetic storms, with a typical time scale of nearly 10 h, are the more global space weather disturbances during which intense auroral substorms occur (Sharma and Veeramani, 2011). There is a close relationship among storm-time auroral magnetic disturbances, transpolar arcs, field-aligned currents and polar substorms that results from coupling between the solar wind and the M–I system. However, these phenomena are limited mainly to the auroral oval regions for most of the time. In high-latitude regions, SW–M–I interactions are mainly manifested as high conductivity along terrestrial magnetic field lines, which have a footprint in the high-latitude ionosphere which forms a closed electric circuit together with the conducting ionosphere. The current or voltage generated through the SW–M dynamo/generator is applied to the high-latitude ionosphere through this circuit (Jayachandran et al., 2003). The present study is focused on the analysis of multiscale entropy using $AE$, $AU$, $AL$ and $PC$ indices which can be considered as statistical descriptors of space storm activity being designed to describe high-latitude/polar geomagnetic fluctuations with