Dynamical Complexity in Swarm SYM-H-like and AE-like Indices Using Information Theory: Further Evidence for Interhemispheric Asymmetry in Earth's Ionosphere

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Complex Systems Methods for Geospace Research (2023)

Space Science Reviews (2023) 219:38
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Complex Systems Methods Characterizing Nonlinear Processes in the Near-Earth Electromagnetic Environment: Recent Advances and Open Challenges

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Abstract
Learning from successful applications of methods originating in statistical mechanics, complex systems science, or information theory in one scientific field (e.g., atmospheric physics or climatology) can provide important insights or conceptual ideas for other areas (e.g., space sciences) or even stimulate new research questions and approaches. For instance, quantification and attribution of dynamical complexity in output time series of nonlinear dynamical systems is a key challenge across scientific disciplines. Especially in the field of space physics, an early and accurate detection of characteristic dissimilarity between normal and abnormal states (e.g., pre-storm activity vs. magnetic storms) has the potential to vastly improve space weather diagnosis and, consequently, the mitigation of space weather hazards.

This review provides a systematic overview on existing nonlinear dynamical systems-based methodologies along with key results of their previous applications in a space physics context, which particularly illustrates how complementary modern complex systems approaches have recently shaped our understanding of nonlinear magnetospheric variability. The rising number of corresponding studies demonstrates that the multiplicity of nonlinear time series analysis methods developed during the last decades offers great potentials for uncovering relevant yet complex processes interlinking different geospace subsystems, variables and spatiotemporal scales.

Keywords Solar wind – magnetosphere – ionosphere coupling · Magnetic storms · Magnetospheric substorms · Space weather · Nonlinear dynamics · Complex systems

Complexity Heliophysics: Living Reviews (2024)

Space Science Reviews (2024) 220:52
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Complexity Heliophysics: A Lived and Living History of Systems and Complexity Science in Heliophysics

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Abstract
This review examines *complexity science* in the context of Heliophysics, describing it not as a discipline, but as a paradigm. In the context of Heliophysics, complexity science is the study of a star, interplanetary environment, magnetosphere, upper and terrestrial atmospheres, and planetary surface as interacting subsystems. Complexity science studies entities in a system (e.g., electrons in an atom, planets in a solar system, individuals in a society) and their interactions, and is the nature of what emerges from these interactions. It is a paradigm that employs systems approaches and is inherently multi- and cross-scale. Heliophysics processes span at least 15 orders of magnitude in space and another 15 in time, and its reaches go well beyond our own solar system and Earth's space environment to touch planetary, exoplanetary, and astrophysical domains. It is an uncommon domain within which to explore complexity science. After first outlining the dimensions of complexity science, the review proceeds in three epochal parts: 1) A pivotal year in the Complexity Heliophysics paradigm: 1996; 2) The transitional years that established foundations of the paradigm (1996-2010); and 3) The emergent literature largely beyond 2010. This review article excavates the lived and living history of complexity science in Heliophysics. It identifies five dimensions of complexity science, some enjoying much scholarship in Heliophysics, others that represent relative gaps in the existing research. The history reveals a grand challenge that confronts Heliophysics, as with most physical sciences, to understand the research intersection between fundamental science (e.g., complexity science) and applied science (e.g., artificial intelligence and machine learning (AI/ML)). A risk science framework is suggested as a way of formulating the grand scientific and societal challenges in a way that AI/ML and complexity science converge. The intention is to provide inspiration, help researchers think more coherently about ideas of complexity science in Heliophysics, and guide future research. It will be instructive to Heliophysics researchers, but also to any reader interested in or hoping to advance the frontier of systems and complexity science.

Keywords Complexity science · Systems science · Data science · Machine learning · Dynamical systems · Transdisciplinary · Networks · Heliophysics · Resilience · Convergence · Philosophy of science · Emergence · Epistemology

Outline

1. Swarm-Derived Indices
   - Swarm Dst
   - Swarm AE
   - Swarm AE-North/AE-South
   - Interhemispheric Asymmetry (I.A.)

2. Information Theory (I.T.)
   - Shannon Entropy
   - Block Entropy
   - Tsallis Block Entropy

3. Information-Theoretic Perspective of I.A.

4. … and two more things

JSWSC Topical Issue: "Swarm 10-year anniversary" (deadline 15 April 2025)

The topical issue (TI) is dedicated to new results from ESA's Swarm mission, in particular to investigations of the Magnetosphere-Ionosphere Coupling, Ionospheric and Thermospheric processes, and their implications for Space Weather, including potential impacts on critical infrastructure.

This issue seeks to bring together cutting-edge studies that shed light on the quiet-time and dynamic ionosphere, including the study of Alfvén waves, Equatorial Spread-F events, plasma bubbles, ULF plasma waves, Field-Aligned Currents etc.

JSWSC

Swarm-derived Indices of Geomagnetic Activity

- Convert B_{NEC} -> B_{MFA}: B_{par} (or B_{total})
- Subtract CHAOS Internal Field Model
- Clean & Interpolate
- Keep only values between certain magnetic latitudes

Index	Magn. Latitude Limits
Dst/SYM-H	[-30°, +30°]
ap	[-60°, -55°] & [+55°, +60°]
AE	[-75°,- 65°] & [+65°, +75°]

- Average to 1-min resolution
- Merge Swarm-A & B measurements
- Low-pass filter (diff. cut-off frequency for each index)
- Linear Transform

AGU ADVANCING EARTH AND SPACE SCIENCE

JGR Space Physics

RESEARCH ARTICLE
10.1029/2021JA029394

Key Points:

- New geomagnetic activity indices based on Swarm magnetic field data are computed similar to standard ground-based indices of Dst, ap, and AE
- Swarm-derived indices show excellent correlations with both the traditional and SuperMAG-derived indices
- Swarm-based AE index enable us to monitor substorm activity also at the southern hemisphere

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Swarm-Derived Indices of Geomagnetic Activity

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Abstract Ground-based indices, such as the Dst, ap, and AE, have been used for decades to describe the interplay of the terrestrial magnetosphere with the solar wind and provide quantifiable indications of the state of geomagnetic activity in general. These indices have been traditionally derived from ground-based observations from magnetometer stations all around the Earth. In the last 7 years though, the highly successful satellite mission Swarm has provided the scientific community with an abundance of high quality magnetic measurements at Low Earth Orbit, which can be used to produce the space-based counterparts of these indices, such the Swarm-Dst, Swarm-ap, and Swarm-AE indices. In this work, we present the first results from this endeavor, with comparisons against traditionally used parameters. We postulate on the possible usefulness of these Swarm-based products for a more accurate monitoring of the dynamics of the magnetosphere and thus, for providing a better diagnosis of space weather conditions.

Plain Language Summary Ground-based geomagnetic activity indices have been used for decades to monitor the dynamics of the Earth's magnetosphere, and provide information on two major types of space weather phenomena, that is, magnetic storm and magnetospheric substorm occurrence and intensity. This study demonstrates how magnetic field data from a Low Earth Orbit satellite mission, like ESA's Swarm constellation, can be used to derive corresponding space-based geomagnetic activity indices. Swarm is unraveling one of the most mysterious aspects of our planet: the magnetic field. The magnetic field and electric currents in and around our planet generate complex forces that have immeasurable impact on everyday life. The comparison of Swarm-based with ground-based indices shows a very good agreement, indicating that Swarm magnetic field data can be used to provide new satellite-based global indices to monitor the level of geomagnetic activity. Given the fact that the official ground-based index for the substorm activity is constructed by data from 12 ground stations solely in the northern hemisphere, it can be said that this index is predominantly northern, while the Swarm-derived substorm activity index may be more representative of a global state, since it is based on measurements from both hemispheres.

Swarm-derived AE

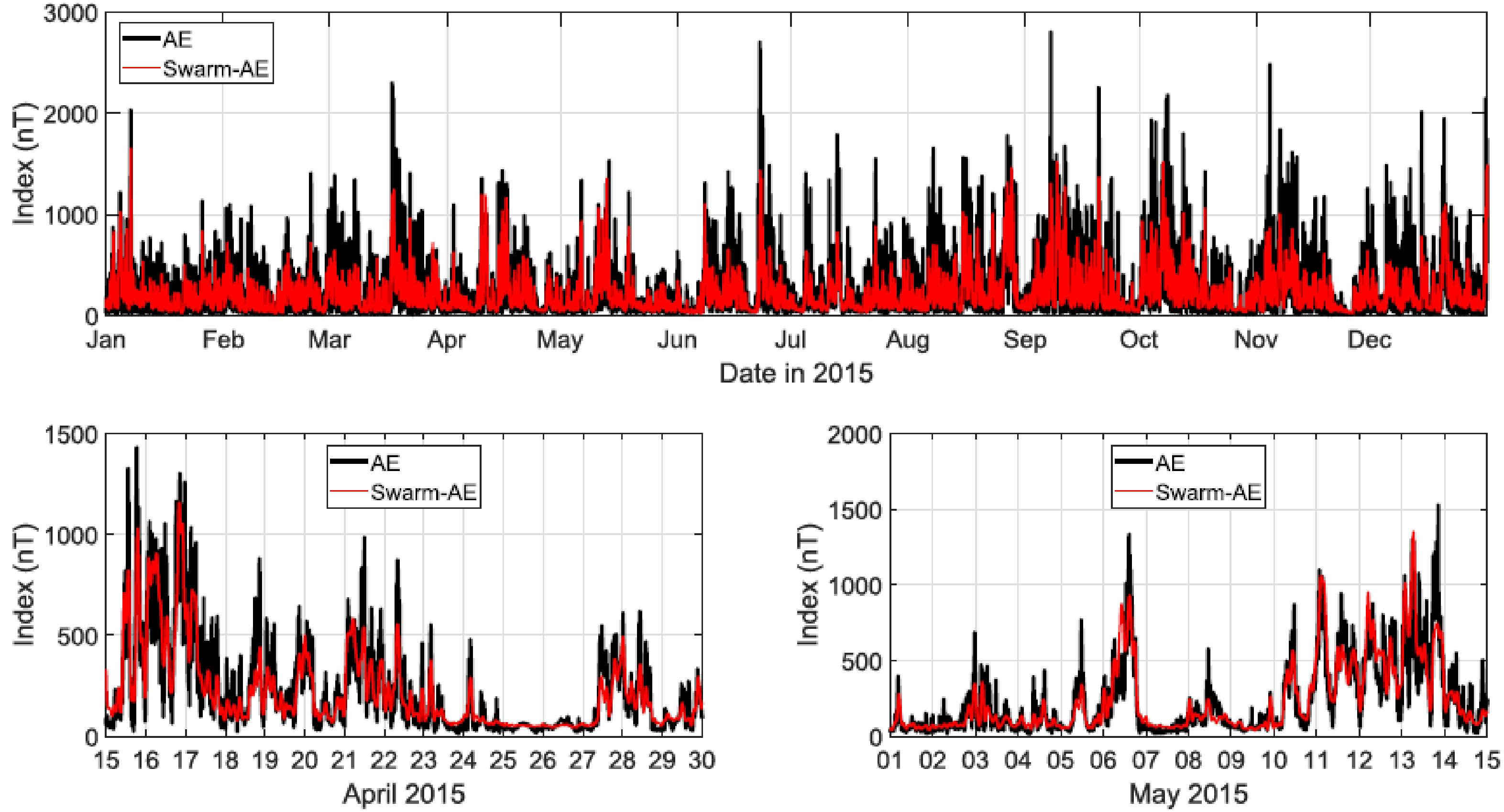
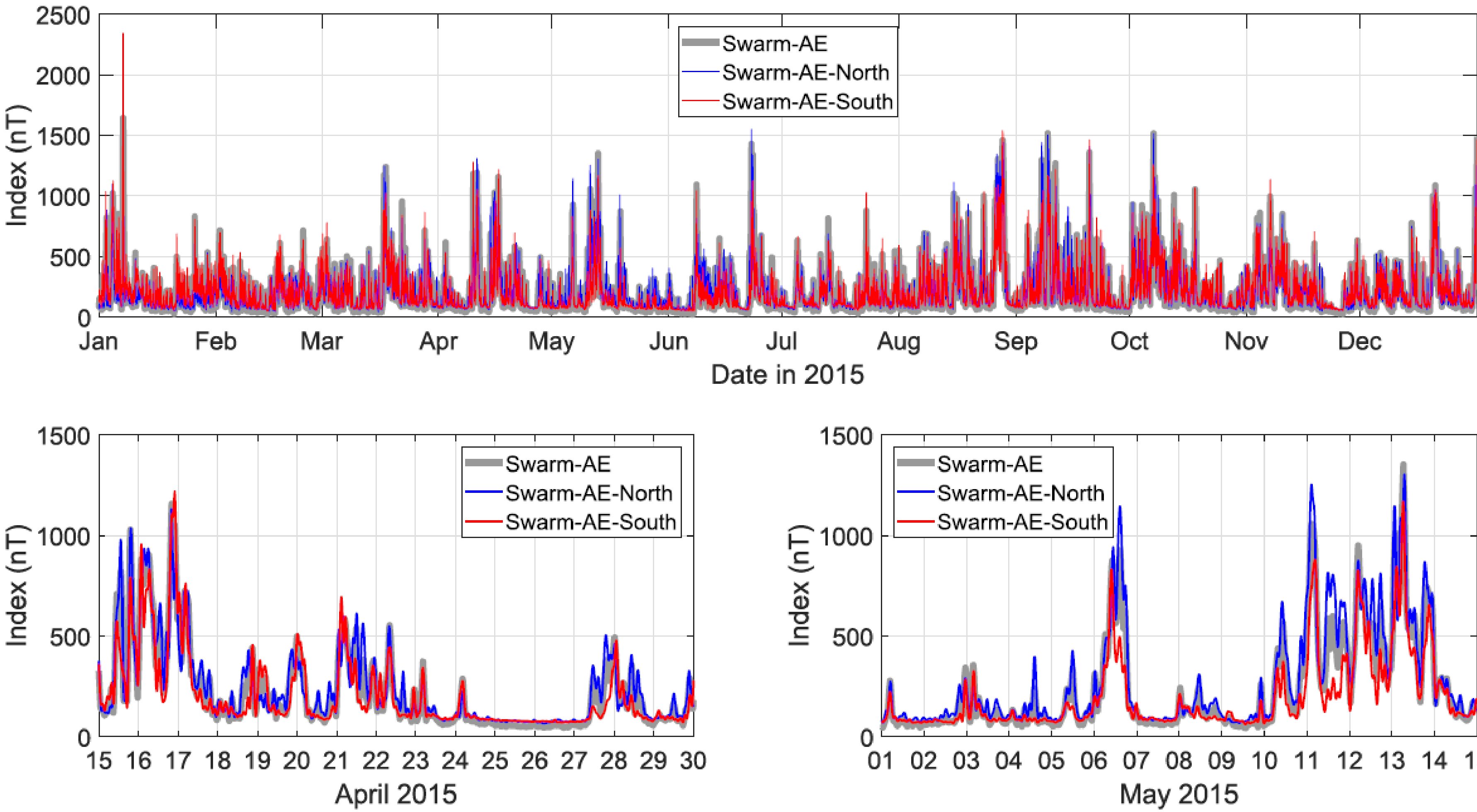


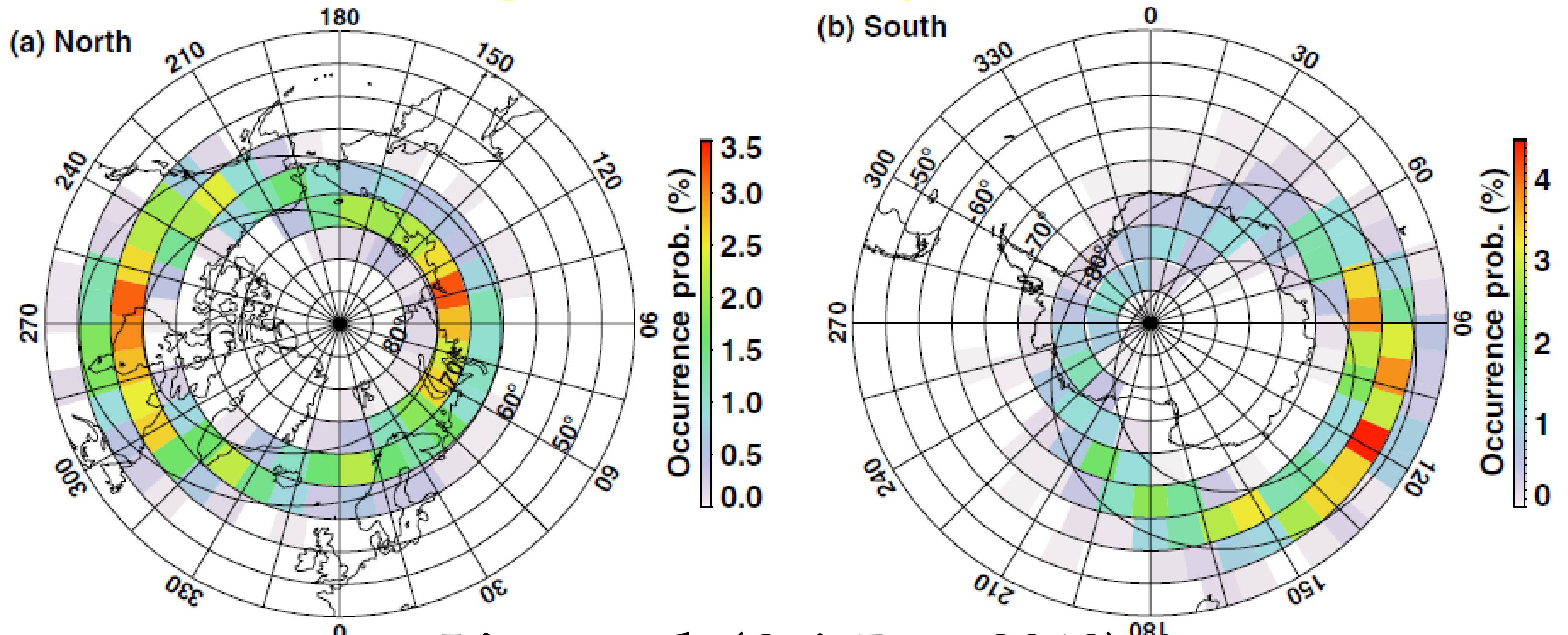
Figure 6. Swarm-derived AE index (red) compared to the standard AE index (black). Top panel shows the entire 12 month period from January 1 to December 31, 2015, while the bottom panels show zoomed pictures from the second half of April (bottom left) and first half of May (bottom right).

Swarm AE-North & AE-South



North-South Asymmetry

- Substorm onset is far from north-south symmetric; it is more likely to be initiated in a dark than a sunlit oval; preferred locations of substorm onsets coincide with the local peak of the Earth's magnetic field (or a minimum in the ionospheric conductivity)



Liou et al. (*Sci. Rep.* 2018)

Figure 1. Azimuthal equidistant projection maps of auroral substorm onset occurrence frequency for the (a) Northern Hemisphere (NH) and (**b**) Southern Hemisphere (SH). The occurrence frequency is derived from 2659 auroral substorm onsets and averaged in equal-area bins (~5° in latitude). Contours of geographic latitudes are drawn every 5° starting from 45° (−45° in the SH) and longitudes are drawn every 15°. Most of the auroral substorm onsets are initiated between 60° and 75° (−60° and −75° in SH) magnetic latitudes, which are plotted in black contours. Continents are overlapped in black. In NH, the peak onset frequency is ~3.5% and is located west of Hudson Bay, center around Churchill, Canada, and Khatanga, Siberia. In SH the peak onset frequency is ~4.5% and is located in the Antarctic ocean between the Australia and the Antarctic continents.

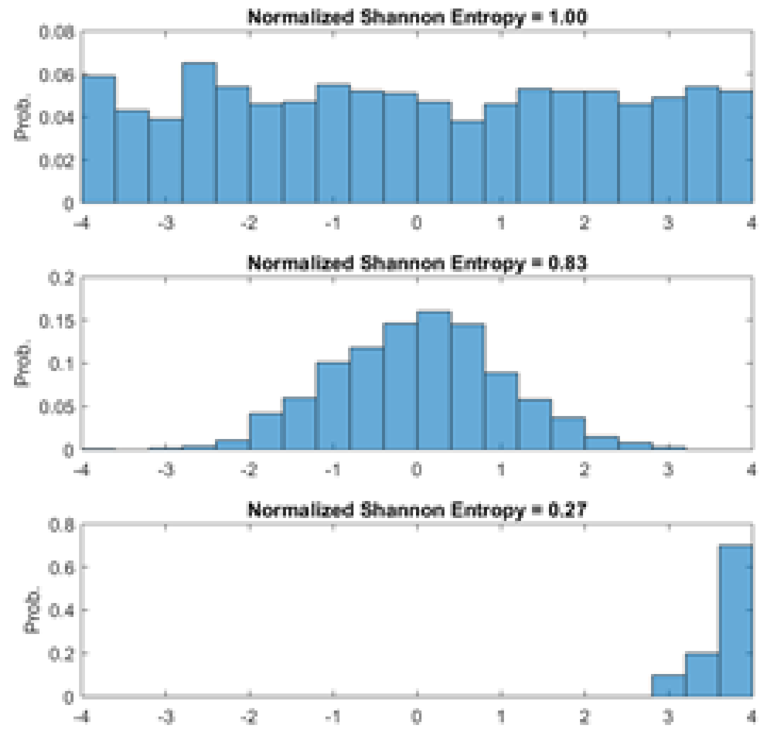
Information Theory

Given p_i the probability of a telecom. system being in a cell 'i' of its phase space, Shannon defined the information produced by it by means of the Boltzmann H theorem, as the entropy

$$H = -\sum_i p_i \cdot \log_b p_i$$

Continuous variables can be "digitized" in order to define these "cells" of the phase space.

This in essence becomes a "histogram entropy" and loses all sense of temporal information.



(Shannon, 1948)

Information Theory

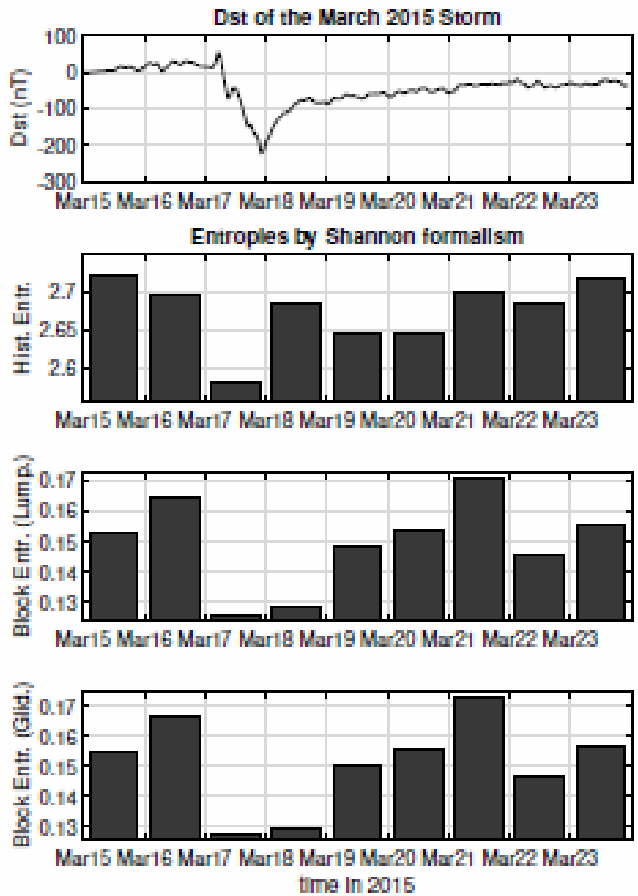


Figure 3. Entropy analysis according to Shannon formalism of the Swarm B total (external) field for the March 2015 magnetic storm.

entropy

MDPI

Article

Dynamical Complexity of the 2015 St. Patrick's Day Magnetic Storm at Swarm Altitudes Using Entropy Measures

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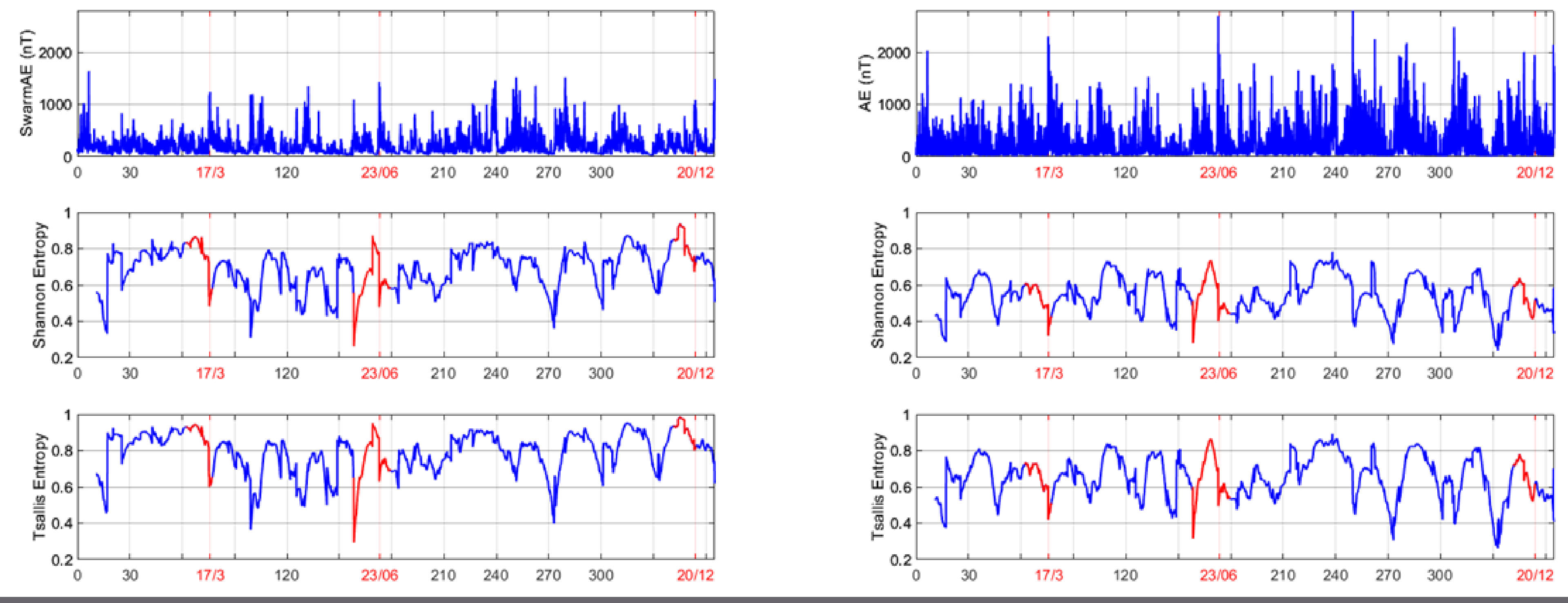
Abstract: The continuously expanding toolbox of nonlinear time series analysis techniques has recently highlighted the importance of dynamical complexity to understand the behavior of the complex solar wind–magnetosphere–ionosphere–thermosphere coupling system and its components. Here, we apply new such approaches, mainly a series of entropy methods to the time series of the Earth's magnetic field measured by the Swarm constellation. We show successful applications of methods, originated from information theory, to quantitatively study complexity in the dynamical response of the topside ionosphere, at Swarm altitudes, focusing on the most intense magnetic storm of solar cycle 24, that is, the St. Patrick's Day storm, which occurred in March 2015. These entropy measures are utilized for the first time to analyze data from a low-Earth orbit (LEO) satellite mission flying in the topside ionosphere. These approaches may hold great potential for improved space weather nowcasts and forecasts.

Keywords: dynamical complexity; entropy; magnetic storm; space weather; Swarm mission

Entropy Analysis of Swarm AE/AE



atmosphere

Article

Investigation of Dynamical Complexity in Swarm-Derived Geomagnetic Activity Indices Using Information Theory

Georgios Balasis [1,*], Adamantia Zoe Boutsi [1,2], Constantinos Papadimitriou [1,2], Stelios M. Potirakis [1,3], Vasilis Pitsis [2], Ioannis A. Daglis [1,2,4], Anastasios Anastasiadis [1] and Omiros Giannakis [1]

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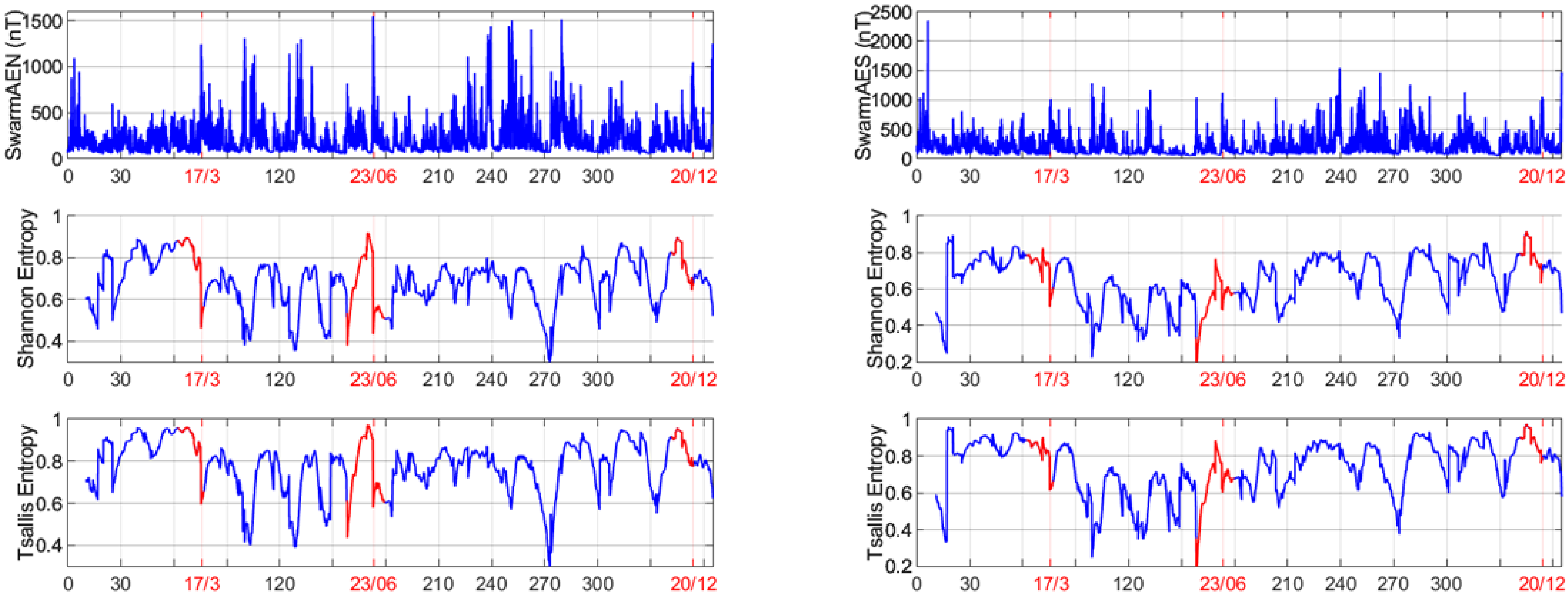
Abstract: In 2023, the ESA's Swarm constellation mission celebrates 10 years in orbit, offering one of the best ever surveys of the topside ionosphere. Among its achievements, it has been recently demonstrated that Swarm data can be used to derive space-based geomagnetic activity indices, similar to the standard ground-based geomagnetic indices monitoring magnetic storm and magnetospheric substorm activity. Recently, many novel concepts originating in time series analysis based on information theory have been developed, partly motivated by specific research questions linked to various domains of geosciences, including space physics. Here, we apply information theory approaches (i.e., Hurst exponent and a variety of entropy measures) to analyze the Swarm-derived magnetic indices from 2015, a year that included three out of the four most intense magnetic storm events of the previous solar cycle, including the strongest storm of solar cycle 24. We show the applicability of information theory to study the dynamical complexity of the upper atmosphere, through highlighting the temporal transition from the quiet-time to the storm-time magnetosphere, which may prove significant for space weather studies. Our results suggest that the spaceborne indices have the capacity to capture the same dynamics and behaviors, with regards to their informational content, as traditionally used ground-based ones.

Keywords: geospace magnetic storms; magnetospheric substorms; Swarm satellites; information theory; wavelets; Hurst exponent; entropies; geomagnetic indices; space weather

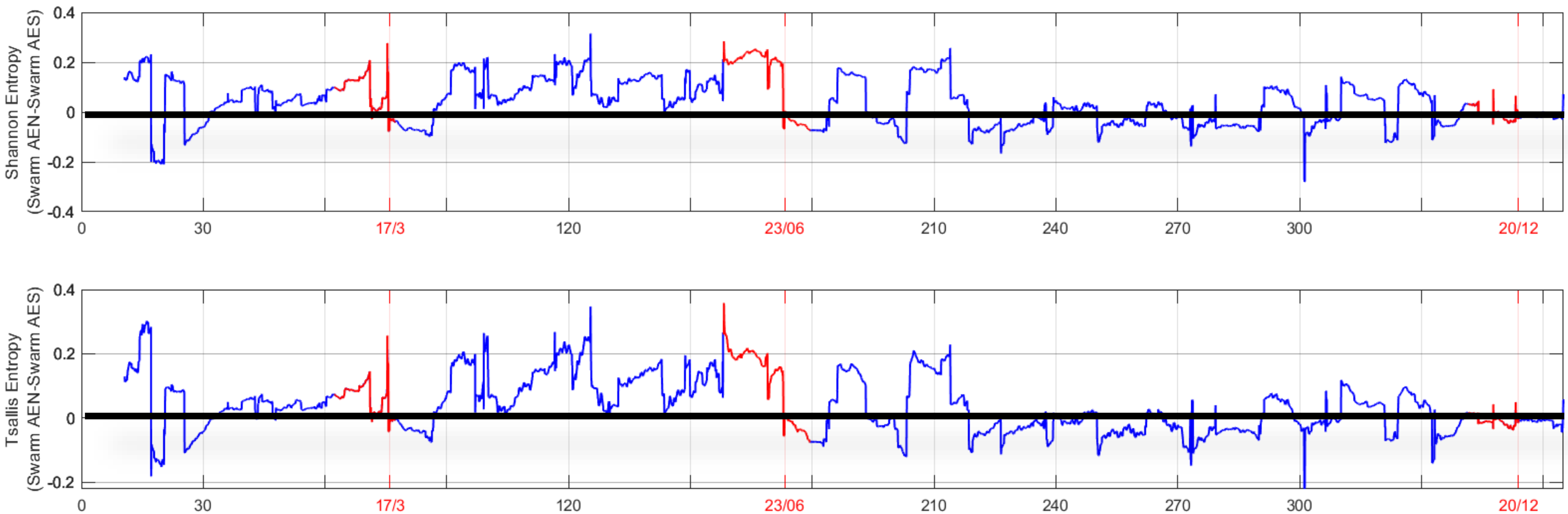
Citation: Balasis, G.; Boutsi, A.Z.; Papadimitriou, C.; Potirakis, S.M.; Pitsis, V.; Daglis, I.A.; Anastasiadis, A.; Giannakis, O. Investigation of dynamical complexity in Swarm-derived geomagnetic activity indices using information theory. *Atmosphere* **2023**, *14*, 890. https://doi.org/10.3390/atmos14050890

Entropy Analysis of Swarm AE-North/Swarm AE-South



Unpublished work

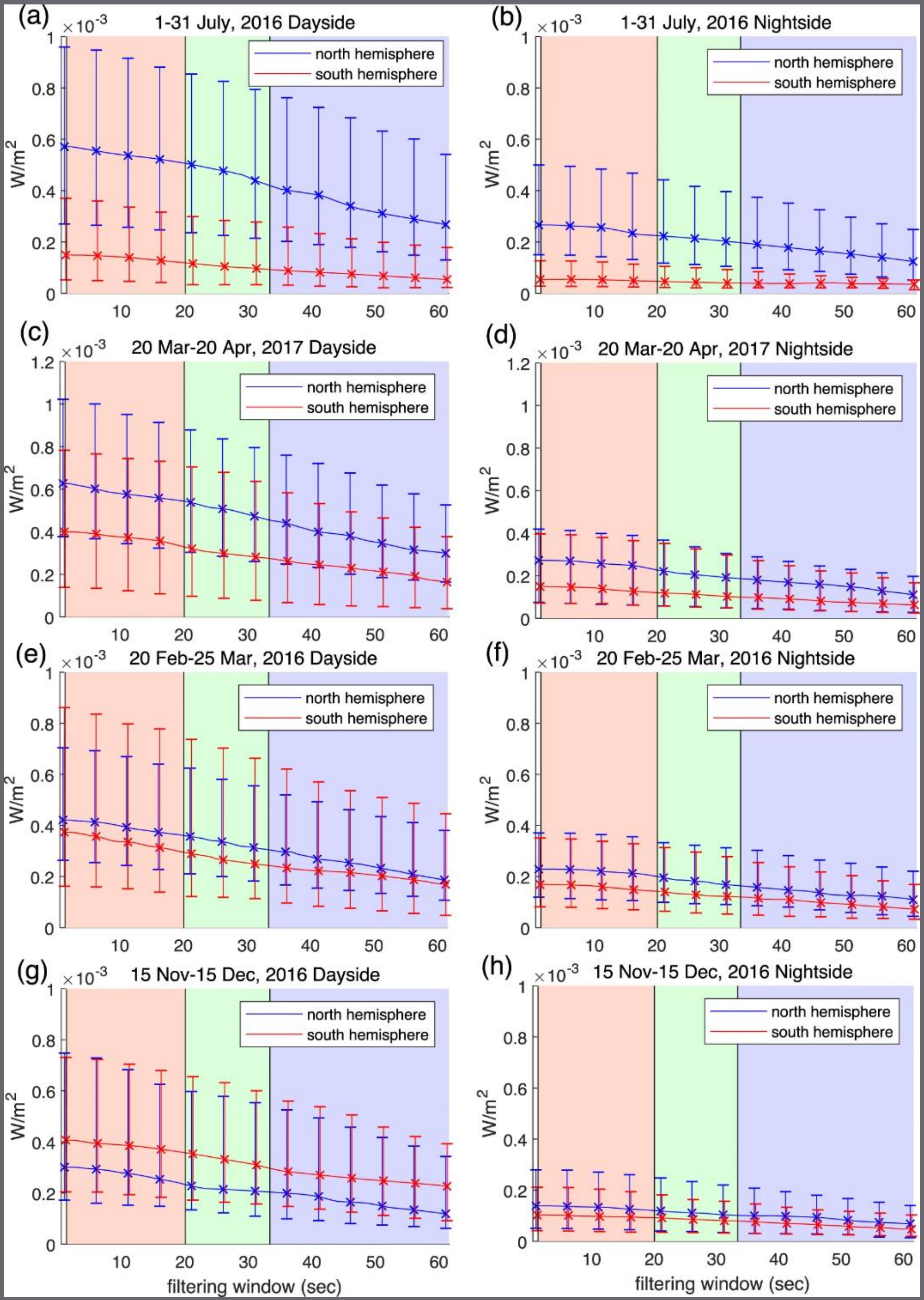
Δ(Entropy) of Swarm-derived Regional AE Indices (North – South)



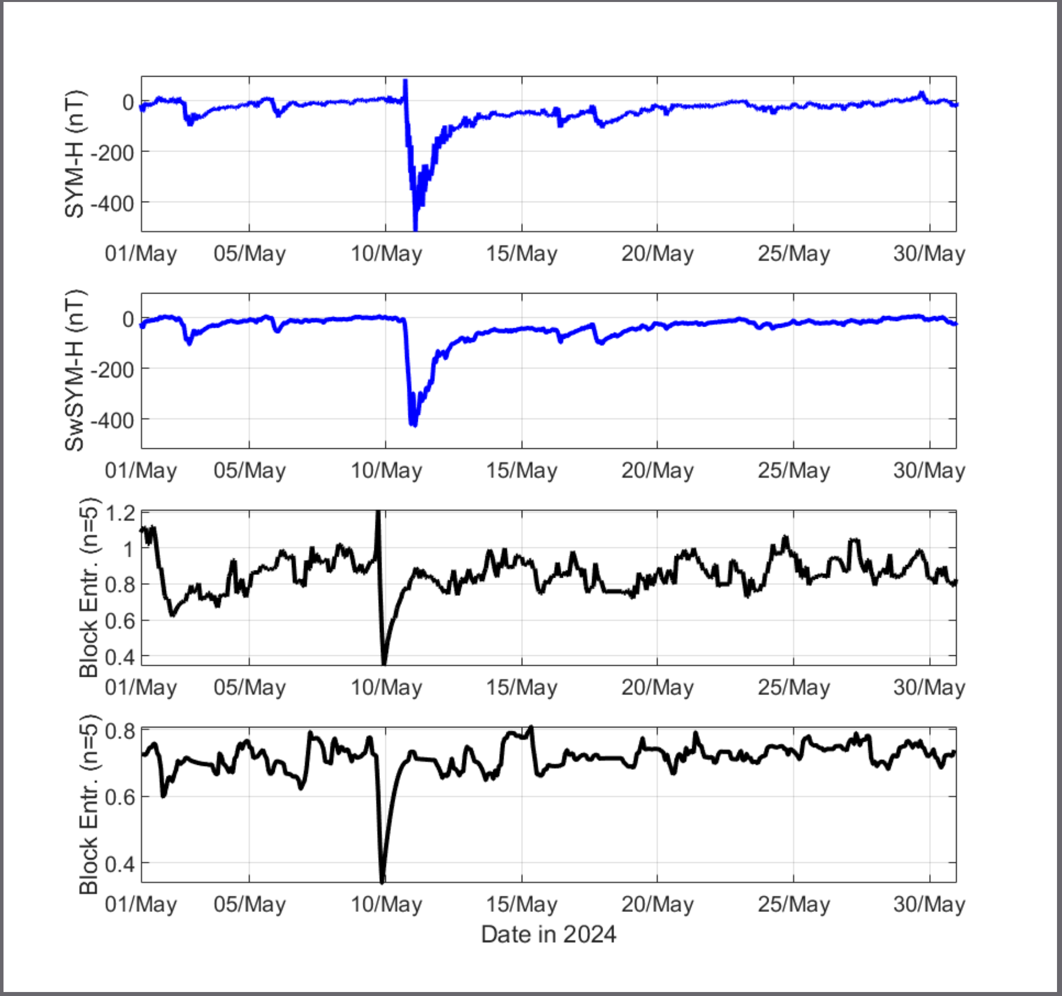
Unpublished work

Northern preference for terrestrial electromagnetic energy input from space weather
(Pakhotin et al., *Nature Communications* 2021)

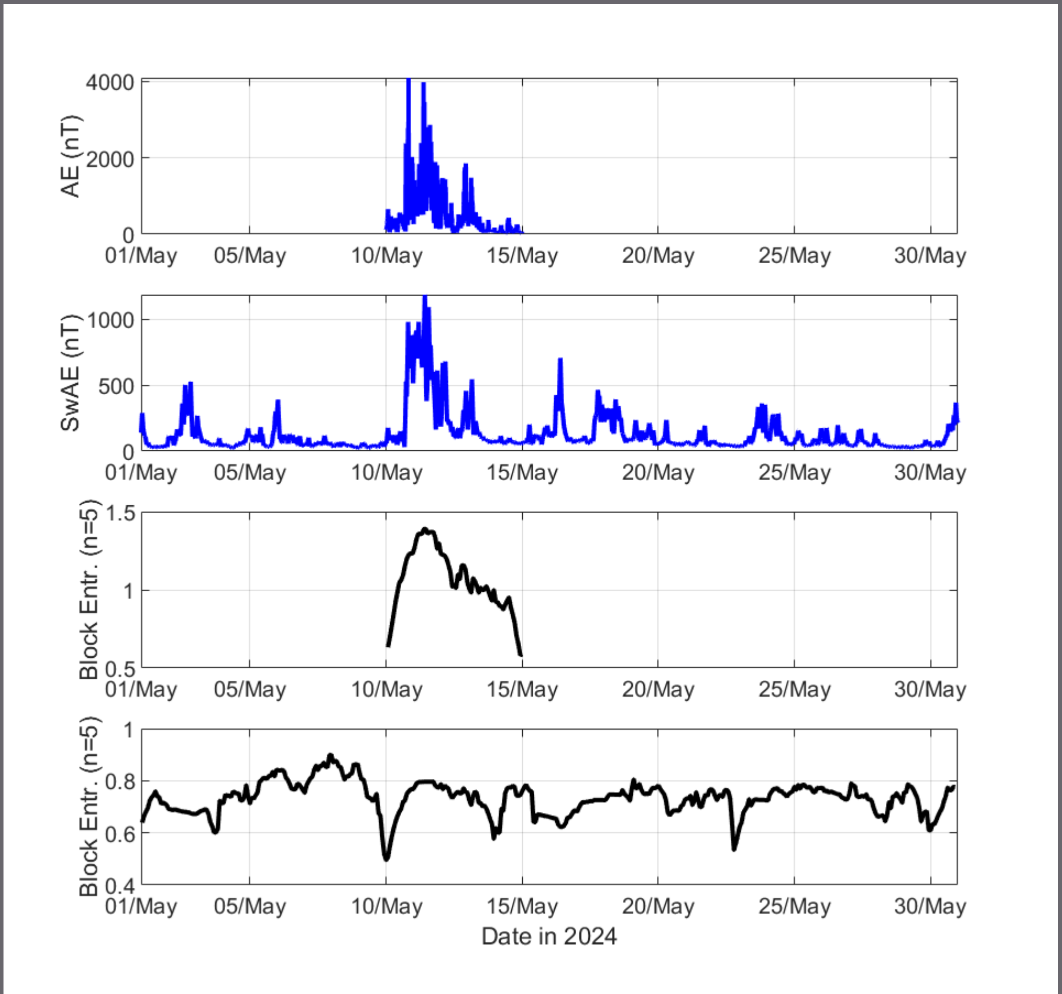
For electromagnetic energy input at Swarm altitudes, northern preference can likely be explained by the relative displacement of the north and south auroral ovals with respect to the Earth's rotation axis, causing effective interhemispheric differential solar illumination of the two auroral ovals.



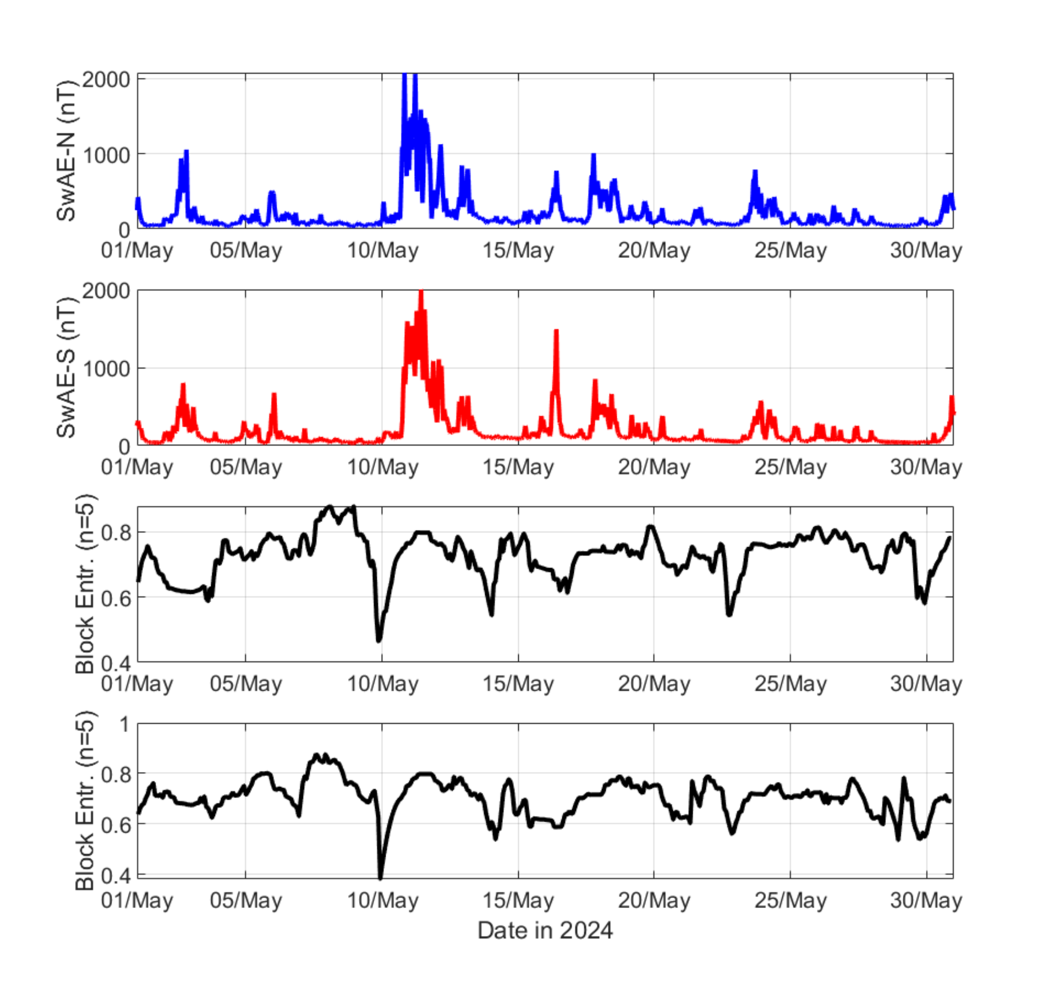
May 2024 superstorm: SYM-H vs Swarm SYM-H



May 2024 superstorm: AE vs Swarm AE



May 2024 superstorm: Swarm AE-North vs Swarm AE-South



May 2024 superstorm: GIC activity indices

entropy

MDPI

Article

Dynamical Complexity in Geomagnetically Induced Current Activity Indices Using Block Entropy

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Abstract: Geomagnetically Induced Currents (GICs) are a manifestation of space weather events at ground level. GICs have the potential to cause power failures in electric grids. The GIC index is a proxy of the ground geoelectric field derived solely from geomagnetic field data. Information theory can be used to shed light on the dynamics of complex systems, such as the coupled solar wind–magnetosphere–ionosphere–ground system. We performed block entropy analysis of the GIC activity indices at middle-latitude European observatories around the St. Patrick's Day March 2015 intense magnetic storm and Mother's Day (or Gannon) May 2024 superintense storm. We found that the GIC index values were generally higher for the May 2024 storm, indicating elevated risk levels. Furthermore, the entropy values of the SYM-H and GIC indices were higher in the time interval before the storms than during the storms, indicating transition from a system with lower organization to one with higher organization. These findings, including the temporal dynamics of the entropy and GIC indices, highlight the potential of this method to reveal pre-storm susceptibility and relaxation processes. This study not only adds to the knowledge of geomagnetic disturbances but also provides valuable practical implications for space weather forecasting and geospatial risk assessment.

Keywords: magnetic storms; geomagnetically induced currents; information theory; block entropy; geomagnetic indices; space weather

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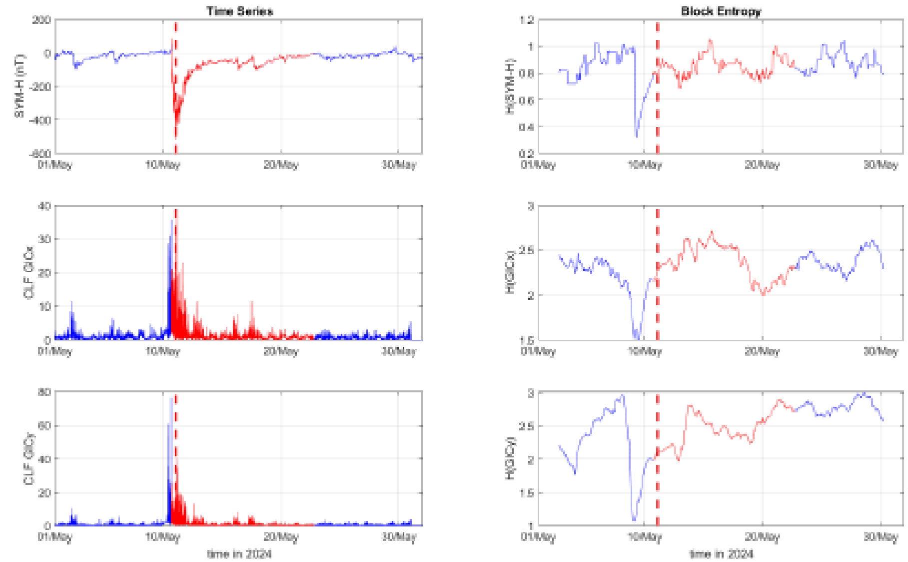

Figure 4. Time series of SYM−H, GICx, and GICy of the Chambon la Forêt observatory (**left**) and corresponding block entropies (**right**) for May of 2024. The red color marks the duration of the storm, while the dashed red line corresponds to the peak of the storm.

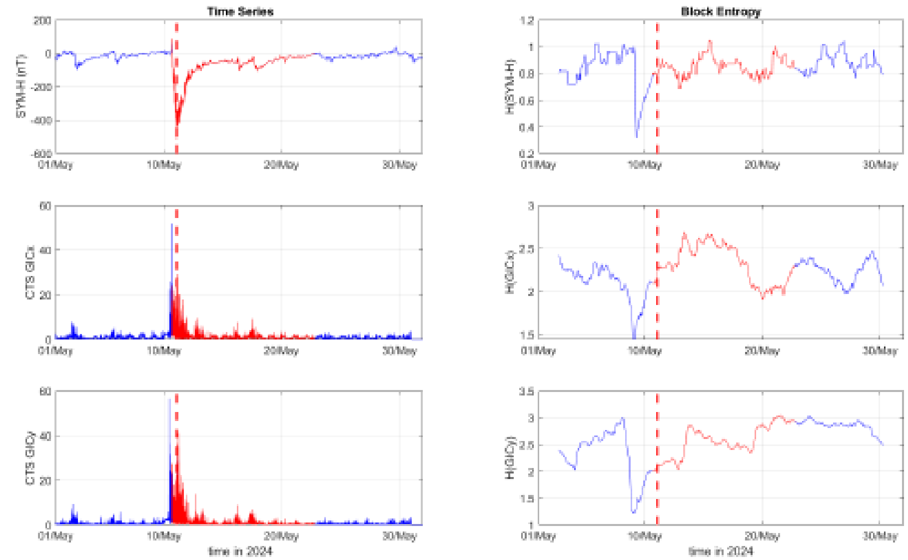

Figure 5. Time series of SYM−H, GICx, and GICy of the Castello Tesino observatory (**left**) and corresponding block entropies (**right**) for May of 2024. The red color marks the duration of the storm, while the dashed red line corresponds to the peak of the storm.

Take Home Message

Complex systems-based methods:

- Have the potential to identify previously unrecognized precursory structures and, thus, contribute to a better understanding of dynamical processes manifested in observable magnetic field fluctuations prior to geospace magnetic storms

- Provide a novel way to anticipating and predicting incipient transitions in the dynamical regime of geomagnetic field variations in time and space