Journal of the Georgian Geophysical Society, e-ISSN: 2667-9973, p-ISSN: 1512-1127
Physics of Solid Earth, Atmosphere, Ocean and Space Plasma, v. 26(2), 2023, pp. 36 - 41

Comparative Analysis of Earth's Climate and Solar and Geomagnetic Activities

[1,2]Luka M. Burdiladze , [1,2]Alexandre P. Gurchumelia , [1,3]Oleg A. Kharshiladze

[1]M. Nodia Institute of Geophysics of the I. Javakhishvili Tbilisi State University, Georgia
[2]E. Kharadze Georgian National Astrophysical Observatory, Tbilisi, Georgia
[3]Department of Physics, I. Javakhishvili Tbilisi State University, Georgia
e-mail: luka.burdiladze108@ens.tsu.edu.ge

ABSTRACT

This paper investigates the intricate relationship between solar activity and Earth's climate and geomagnetic activity, utilizing data spanning from 1974 to 2021. Analyzing monthly averaged measures such as Wolf number, total solar irradiance (TSI), global ocean temperature anomalies (GOTA), and Ap index of geomagnetic disturbances, we employ various methods including linear correlation analysis, recurrence quantification analysis (RQA), and cross wavelet transform (XWT). The study reveals a periodically varying correlation between TSI and GOTA with periodicity of approximately 12 years, emphasizing the intricate interplay between solar activity and climate. The recurrence plots and RQA unveil periodicity and phase transition after 1995. XWT also show multifrequency transient event ocurring in 1996. Collectively these findings suggest that the transient event might be related to the phase transition around this time period in the studied system.

Key words: *Sun-Earth connections, solar activity, ocean temperature, Wolf number, RQA, correlation analysis, cross wavelet analysis.*

Introduction

Solar activity plays a pivotal role in governing various phenomena associated with space weather. The intricate processes occurring on the sun not only influence space weather dynamics but also exert a significant impact on Earth's climate. This is why the study of solar activity and Sun-Earth interactions is important. Previous results were obtained in the paper [1] and the present article is an extension of the initial research.

The characterization of solar activity relies on indices designed to quantify its various facets. One such index is wolf number [2] which is related to number of sunspots on the visible surface of the Sun by the formula $R=k(10G+N)$ where N is the number of sunspots, G is the number of sunspot groups and k is correction coefficient. Its dynamic range spans from 0 to 450 within a 24-hour period.

There also exists another solar activity index called total solar irradiance (TSI) [3], which is the flux of solar electromagnetic radiation measured at 1 A.U. (Astronomical Unit) distance and integrated over all wavelengths [4,5]. In SI units TSI is measured in Wm^{-2}.

The Ap index [6] is a daily measure for magnetic activity of Earth's magnetic field. It is derived from K-index, integer ranging from 0 to 9 that describes disturbance in the horizontal component of the magnetic field. Ap is calculated by converting three-hour K-values into a simpler scale called the a-index, and then averaging eight of these a-values for the day. The Ap index, as an averaged planetary A-index, provides a helpful picture of geomagnetic conditions.

We also use global ocean temperature anomalies (GOTA) [7] as climate data. All given datasets are plotted in figure 1.

The study [8] employed wavelet coherence analysis to reveal an in-phase resonance oscillation between TSI and sunspot number (SSN), with SSN identified as a primary driver for TSI's periodic variation. Additionally, intermittent resonance periodicity was observed in the 2–6 month band during the maximum time of solar cycles, indicating a more complex and unsteady relationship.

Wavelet coherence analysis was also used to explore the relationship between TSI and the atlantic multidecadal oscillation (AMO) [9]. The results reveal significant coherence between TSI and AMO, providing insights into the long-term variations of surface temperature and their connection to solar activity cycles. The paper emphasizes the importance of understanding this coherence for improved comprehension of recent climate changes and enhancing long-term forecasting.

Analysis methods

From the group of statistical tools, we use linear correlation analysis, which determines the time dependance of correlation coefficient between two time series within a window of fixed length sliding forward in time. Correlation coefficient varies from -1 to 1. This analysis was performed on pairs of time series: 1) TSI and temperature and 2) TSI and wolf number.

Recurrence quantification analysis (RQA) is used to study complexity of a system. Along with the construction of the recurrent diagram quantitative measurements are evaluated: recurrence rate (RR), determinism (DET) and entropy (ENTR) [10].

Cross wavelet transform (XWT) introduced in [11] is an extension of the continuous wavelet transform applied to two different time series simultaneously. It allows the exploration of common power and phase relationships between the two series in the time-frequency space. The XWT helps identify whether specific features in one time series are consistently related to features in another series, providing insights into potential causal relationships or shared influences. Wavelet coherence (WTC) also introduced in [11] is a measure that quantifies the degree of coherence or correlation between two time series across different scales (frequencies) and times. It is derived from the XWT. While XWT reveals areas of common power, WTC provides a more refined analysis by indicating not only the presence of common power but also the consistency or phase locking of this power over time. WTC is particularly useful for uncovering locally phase-locked behavior between the two time series, indicating whether their oscillatory patterns are synchronized or correlated at specific frequencies and time intervals.

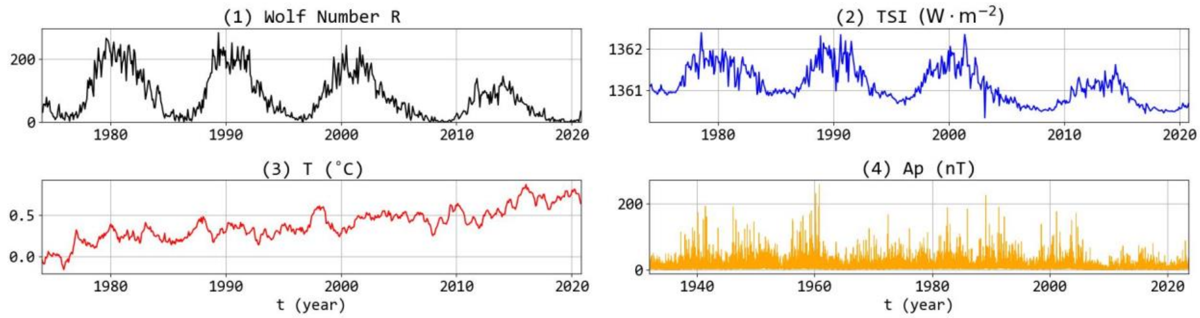

Fig. 1. (1) wolf number, (2) TSI, (3) GOTA, all averaged monthly and (4) daily Ap index.

Results

Linear correlation analysis of Fig. 4(2) reveals a periodically varying correlation between TSI and GOTA, accompanied by a linearly decreasing trend. The observed period oscillation in correlation spans approximately 12 years, while the trend slope registers at around -0.01 years^{-1}.

Fig. 4(4) shows strong correlation of above 0.6 between TSI and wolf number. Furthermore, in 1983 correlation starts to increase to levels above 0.75. Around this time, the 11-year solar activity begins to enter a new minimum. Recurrence diagram of TSI and wolf number in Fig. 2(1,2) shows that they both have periodic and noisy components. After about 2000 years, the black areas on both recurrence diagrams become larger, which is related to the beginning of the activity minima [12].

The DET for monthly Wolf number is close to 1. Evolution of TSI's DET shows that TSI is more deterministic during solar activity minima. we can conclude this if we observe DET in Fig. 2(4). Its value is lower during 1980-1990 and increases after 2000. From recurrence plot in Fig. 2(2) one can see that periodicity in the system is regular from time range of 1974 – 1995 and then also from 2005 – 2020, however these two time ranges do not appear to produce regular recurrence patterns with each other (bottom right and top left quarters of the plot). Together with this, white narrow and short vertical lines around year 1996 in the bottom left quarter of the plot indicate that some sort of phase transition has occured roughly around 1996.

Cross wavelet analysis shows that wolf number and TSI are coherent in different time regions and on different time scales. Especially, the modes with a period of about 11 years have the longest coherence. In addition, for the given time range of 1974 – 2021, phase difference between the modes of the 11-year period is constant and not equal to 0. Arrow orientation in figures 4 indicates phase difference. This means that there is a delay between the main periodic activity of the Sun and its radiation measured on Earth. There are less time intervals and scales of coherence for TSI and GOTA. they are given in Fig. 3(2).

In all coherence plots in Fig. 3 except Fig. 3(2) pronounced horizontal line with period of 3.2 years starting from 1970 and ending at 1994 can be seen. Furthermore multifrequency oscillations are observed during the end of this time range, especially on Fig. 3(1), indicating transient behavior, which is close to the phase transition point seen on the recurrence plot Fig. 2(2).

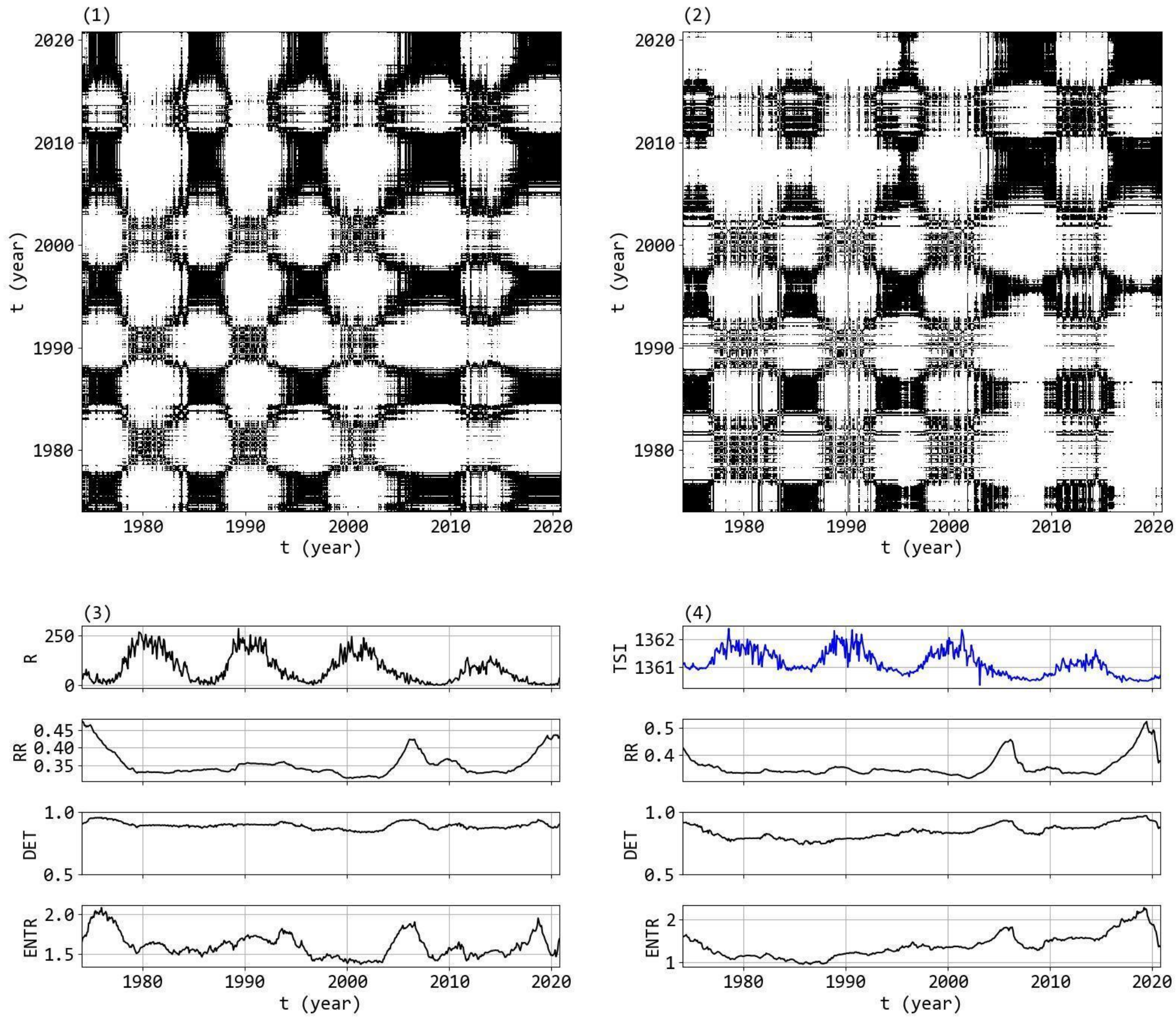

Fig 2. (1) - (2) Recurrence diagrams of wolf number and TSI. (3) - (4) Dynamics of RQA measures generated from (1)-(2). The window size is 10 years.

Conclusions

Correlation analysis of solar activity and Earth temperature data shows that correlation between them changes with a period of about 12 years and also decreases linearly. For the given time period (1974-2021) correlation between TSI and wolf number is positive and increases after 1983. RQA of wolf number and TSI shows that the determinism of wolf number is close to 1 and the determinism of TSI starts to increase after 1990. TSI and wolf number are characterized by high coherence and their main 11-year activity modes has constant nonzero phase difference.

The recurrence plots unveils a regular periodicity in the system during the time spans of 1974–1995 and 2005–2020. However, intriguingly, these two periods do not exhibit regular recurrence patterns with each other. With further features on the recurrence plot for 1996 this suggests a phase transition occurring during that time. Coherence plots reveal a pronounced horizontal line with a 3.2-year period, extending from 1970 to 1994. Towards the end of this timeframe, multifrequency oscillations indicate transient behavior closely aligned with the observed phase transition in the recurrence plot. These findings collectively suggest that some sort of transient event cause a phase transition in the studied system.

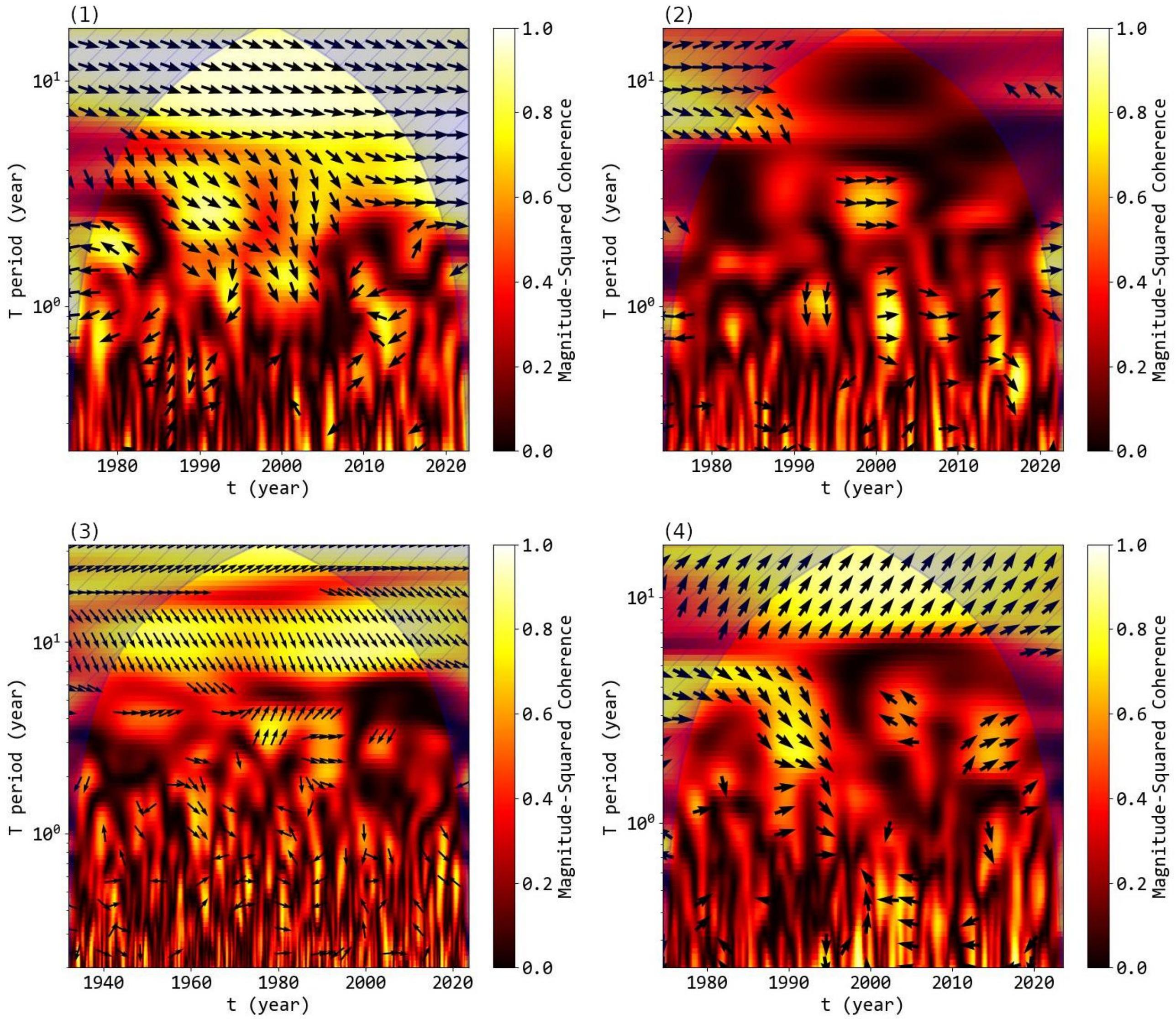

Fig. 3. (1) Wavelet coherence between wolf number and TSI, (2) TSI and GOTA, (3) Wolf number and Ap index and (4) TSI and Ap index.

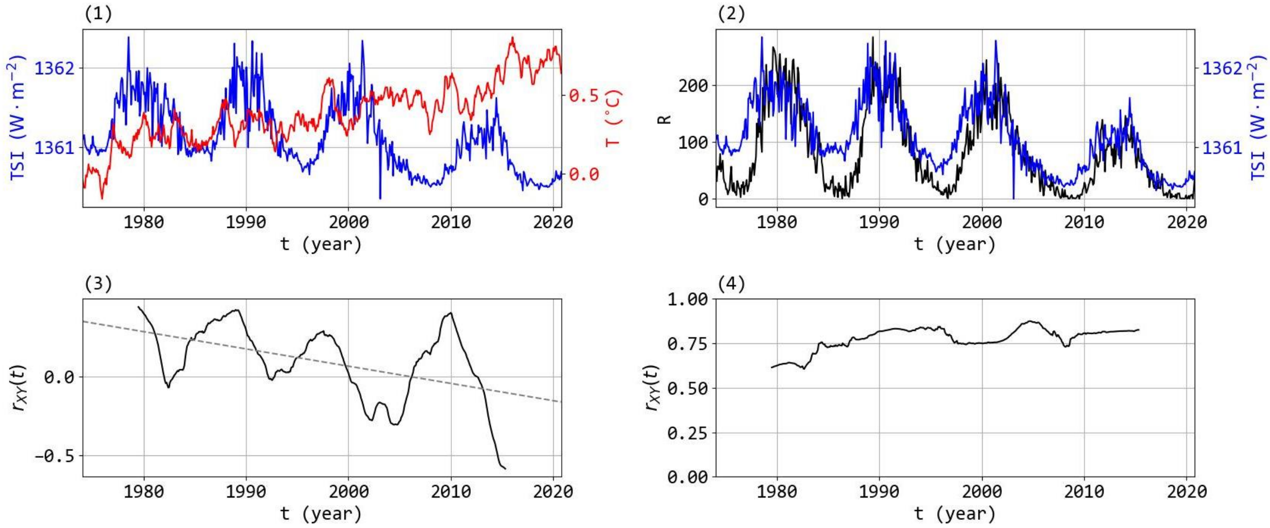

Fig. 4. (1) Monthly data of TSI and GOTA. (2) Monthly data of wolf number and TSI. (3) Evolution of correlation between TSI and temperature and its linear trend (dashed gray line). The window size is 11 years. (4) Evolution of correlation between wolf number and TSI. The window size is 11 years.

References

[1] Burdiladze L., Kharshiladze O., Modebadze Z. Analysis of Solar Activity and Earth's Climate. International Scientific Conference "Geophysical Processes in the Earth and its Envelopes". Proceedings, ISBN 978-9941-36-147-0, Publish House of Iv. Javakhishvili Tbilisi State University, November 16-17, 2023, pp. 210-212. http://dspace.gela.org.ge/bitstream/123456789/10438/1/51_IG_90.pdf

[2] Sunspot / Wolf Number from WDC-SILSO, Royal Observatory of Belgium, Brussels: https://sidc.be/SILSO/datafiles.

[3] Krivova N. The Sun and the Earth's Climate". Total Solar Irradiance Data: https://www2.mps.mpg.de/projects/sun-climate/data.html.

[4] Stickler G., Kyle L. Educational Brief-Solar Radiation and the Earth System. National Aeronautics and Space Administration, 2016.

[5] Carroll B. W., Ostlie, D. A. An Introduction to Modern Astrophysics. Cambridge University Press., 2017.

[6] Ap Index Data Obtained from Kyoto University Webpage: https://wdc.kugi.kyoto-u.ac.jp/kp/index.html.

[7] NOAA National Centers for Environmental Information, Climate at a Glance: Global Time Series, Published November 2023, Retrieved from: https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/time-series .

[8] Yang R., Cao J., Huang W., Nian A. Cross Wavelet Analysis of the Relationship Between Total Solar Irradiance and Sunspot Number. Chinese Science Bulletin, 55, 2010, pp. 2126-2130.

[9] Kolev V., Chapanov Y. Wavelet Coherence of Total Solar Irradiance and Atlantic Climate. arXiv preprint arXiv:2305.02319, 2023.

[10] Marwan N., Romano M. C., Thiel M., Kurths J. Recurrence plots for the analysis of complex systems. Physics reports, 438(5-6), 2007, pp. 237-329. http://www.recurrence-plot.tk/.

[11] Grinsted A., Moore J. C., Jevrejeva S. Application of the Cross Wavelet Transform and Wavelet Coherence to Geophysical Time Series. Nonlinear Processes in Geophysics, 11(5/6), 2004, pp. 561-566.

[12] Stangalini M., Ermolli I., Consolini G., Giorgi F. Recurrence quantification analysis of two solar cycle indices. Journal of Space Weather and Space Climate, 7, A5, 2017.

დედამიწის კლიმატის, მზისა და გეომაგნიტური აქტოვობების შედარებითი ანალიზი

ლ. ბურდილაძე, ა. ღურჭუმელია, ო. ხარშილაძე

რეზიუმე

ამ ნაშრომში გამოკვლეულია მზის აქტივობას, დედამიწის კლიმატსა და გეომაგნიტურ აქტივობას შორის რთული კავშირი 1974 წლიდან 2021 წლამდე არსებული მონაცემების გამოყენებით. გაანალიზებულია თვიური საშვალო მაჩვენებლები, როგორებიცაა ვოლფის რიცხვი, მზის მუდმივა (TSI), ოკეანის გლობალური ტემპერატურის ანომალიები (GOTA) და Ap ინდექსი გეომაგნიტური შეშფოთებებისთვის. გამოყენებულია სხვადასხვა მეთოდები, მათ შორის წრფივი კორელაციური ანალიზი, რეკურენტული რაოდენობრივი ანალიზი (RQA) და კროს-ვეივლეტ გარდაქმნა (XWT). კვლევა ავლენს პერიოდულად ცვალებად კორელაციას TSI-სა და GOTA-ს შორის დაახლოებით 12 წლის პერიოდულობით, რაც ხაზს უსვამს მზის აქტივობასა და კლიმატს შორის რთულ დინამიურ კავშირს. რეკურენტობის გრაფიკმა და RQA-მ გამოავლინა პერიოდულობა და ფაზური გადასვლა 1995 წლის შემდეგ. XWT ასევე აჩვენებს მრავალსიხშირულ ტრანზიენტულ მოვლენას, რომელიც მოხდა 1996 წელს. ერთობლივად ეს დაკვირვებები იძლევა ვარაუდის საფუძველს, რომ შესწავლილ სისტემაში ტრანზიენტული მოვლენა შესაძლოა დაკავშირებული იყოს ფაზურ გადასვლასთან ამ პერიოდის განმავლობაში.

საკვანძო სიტყვები: მზე-დედამიწის კავშირი, მზის აქტივობა, ოკეანის ტემპერატურა, ვოლფის რიცხვი, RQA, კორელაციური ანალიზი, კროს-ვეივლეტ ანალიზი.

Сравнительный анализ климата Земли, солнечной и геомагнитной активности

Л. Бурдиладзе, А. Гурчумелия, О. Харшиладзе

Резюме

В этой статье исследованы сложные взаимосвязи между солнечной активностью, климатом и геомагнитной активностью Земли, с использованием данных за период с 1974 по 2021 гг. Мы анализируем такие среднемесячные показатели, как число Вольфа, полное солнечное облучение (TSI), глобальные аномалии температуры океана (GOTA) и Ap индекс геомагнитных возмущений, используя различный методы, в том числе, линейный корреляционный анализ, количественный рекуррентный анализ (RQA) и кросс-вейвлет-преобразование (XWT). Исследование выявило периодически меняющуюся корреляцию между TSI и GOTA с периодичностью примерно 12 лет, подчеркивая динамическое взаимодействие между солнечной активностью и климатом. Графики рекуррентности и RQA раскрывают периодичность и фазовый переход после 1995 года. XWT также показывает многочастотное переходное событие, произошедшее в 1996 году. В совокупности эти результаты позволяют предположить, что переходное событие может быть связано с фазовым переходом примерно в этот период времени в изучаемой системе.

Ключевые слова: солнечно-земные связи, солнечная активность, температура океана, число Вольфа, RQA, корреляционный анализ, кросс-вейвлет анализ.