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ANALYSIS OF SOLAR ACTIVITY AND EARTH'S CLIMATE

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Abstract. In this paper we study the solar activity and its influence on the earth's climate by analyzing the following data (averaged monthly): Wolf Number, Total Solar Irradiance (TSI) and Global Ocean Temperature Anomalies from 1974 to 2021. We use the following data analysis methods: linear correlation analysis, Recurrence Quantification Analysis (RQA) and Cross Wavelet Transform.

Keywords: Sun-Earth connections, Solar Activity, Ocean Temperature, RQA, Correlation Analysis, Cross Wavelet Transform.

Introduction: Solar activity is responsible for many phenomena related to space weather. Processes that occur on the sun govern both space weather and Earth's climate, which is why the study of solar activity and Sun-Earth interactions is important. Solar activity is characterized by activity indexes. One of them is Wolf Number which is related to number of sunspots on the visible surface of the Sun by the formula $R = k(10G + N)$. R is Wolf Number, N is the number of sunspots, G is the number of sunspot groups and k is correction coefficient. Within 24 hours, the value of Wolf Number can become from 0 to 450. Also there exists another solar activity index called Total Solar Irradiance (TSI), which is the flux of solar electromagnetic radiation measured at 1 A.U. (Astronomical Unit) distance and integrated over all wavelengths[1,2]. The unit of Total Solar Irradiance is W/m^2 (watts per square meter) in SI units. We also use Global Ocean Temperature Anomalies as climate data. All three data are from 1974 to 2021 and are averaged monthly (Fig. 1(1,2,3)).

Data analysis methods: From the group of statistical tools, we use linear correlation analysis, which determines the correlation coefficient between two time series. It changes continuously from -1 to 1. In the analysis, we take a sliding window of fixed length, calculate the correlation coefficient and how it changes over time for several pairs of data: 1) TSI and temperature, 2) Wolf Number and TSI. Recurrence Quantification Analysis (RQA) is used to study complexity of a system. Along with the construction of the recurrent diagram quantitative measurements are evaluated:

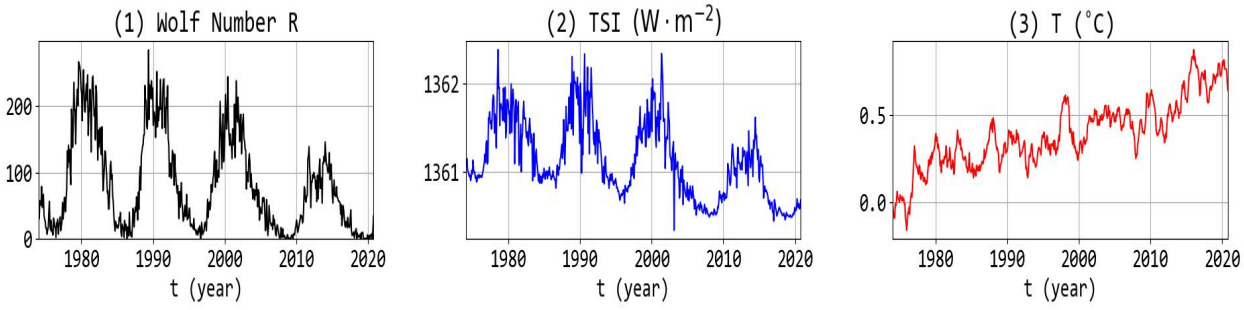

Fig. 1. (1) Wolf Number [6], (2) TSI[7] and (3) Global Ocean Temperature Anomalies[8] all averaged monthly.

Recurrence Rate (RR), Determinism (DET), Entropy (ENTR)[3]. As the extended usage of wavelet analysis, cross wavelet transform is applied to the calculation of common periods and phase angles of two time series[4]. We also use this method for different pairs of time series from Fig. 1.

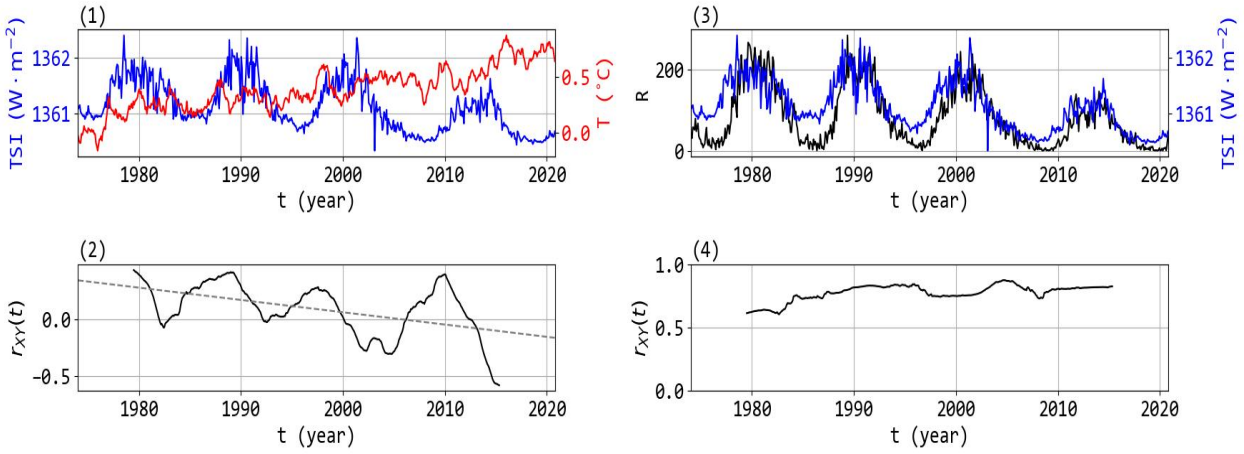

*Fig. 2. (1) Monthly data of TSI and g*lobal ocean temperature anomalies. *(2) Evolution of correlation between TSI and temperature and its linear trend (dashed gray line). The window size is 11 years. (3) Monthly data of Wolf Number and TSI. (4) Evolution of correlation between Wolf Number and TSI. The window size is 11 years.*

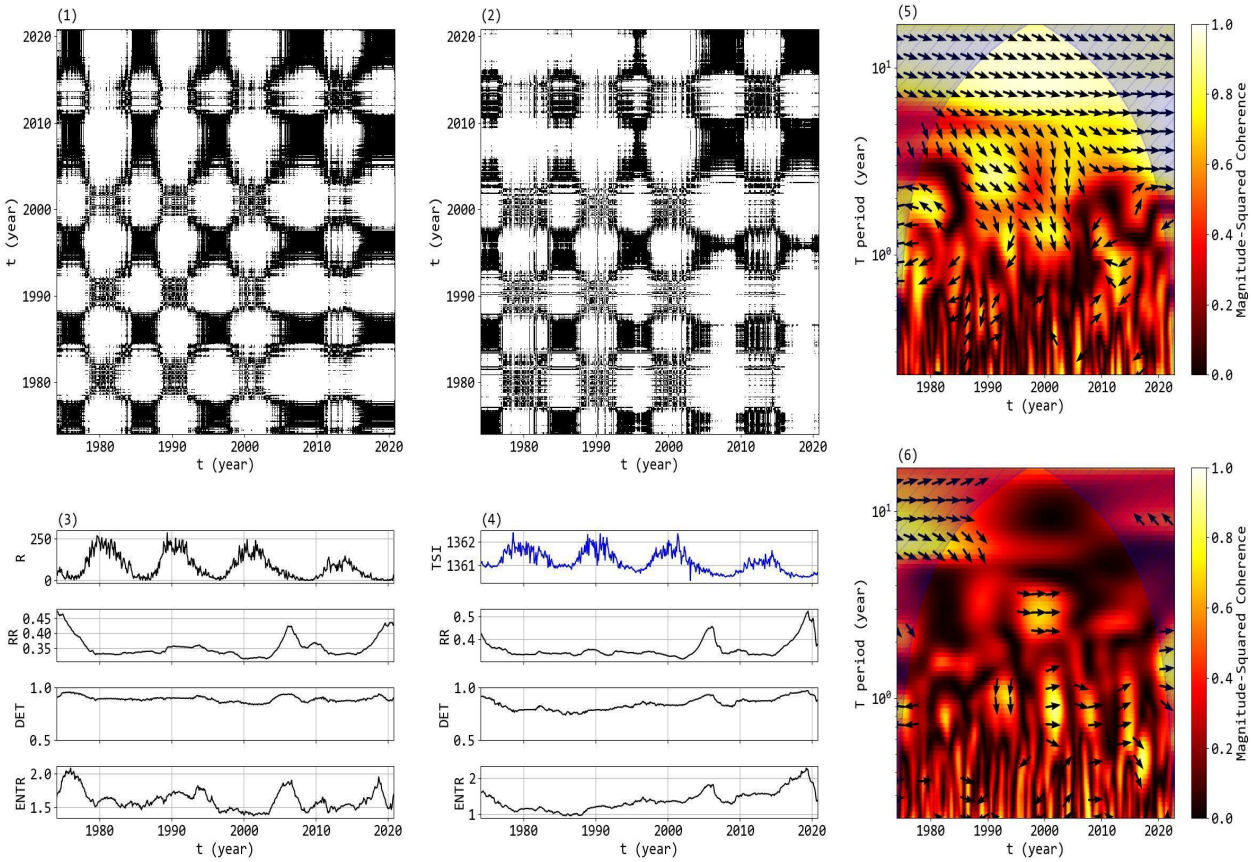

Fig 3. (1)-(2) Recurrence Diagrams of Wolf Number and TSI. (3)-(4) Dynamics of RQA measures generated from (1)-(2). the window size is 10 years. (5) Wavelet coherence of Wolf Number and TSI. (6) Wavelet coherence of TSI and global ocean temperature anomalies.

Results: linear correlation analysis of Fig. 2(1) shows that the correlation between TSI and global ocean temperature varies periodically and also has a linear decreasing trend. The period of correlation is roughly 12 years and the tangent of linear trend is $\tan(\alpha) \approx -0.01\,\text{year}^{-1}$. Analysis of Fig. 2(2) shows strong correlation between

TSI and Wolf Number. Furthermore, in 1983 correlation starts to increase. Around this time, the 11-year solar activity begins to enter a new minimum. Recurrence Diagram of TSI and Wolf Number (Fig. 3(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 [5]. 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 on Fig. 3(4). Its value is lower during 1980-1990 and increases after 2000. Cross Wavelet Analysis shows that Wolf Number and Total Solar Irradiance 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 period (1974-2021), phase difference between the modes of the 11-year period is constant and not equal to 0 (phase differences are indicated by the orientation of the arrows on Fig. 3(5)). 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 the coherence of TSI and global ocean temperature. they are given on Fig. 3(6).

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. Wavelet coherence of TSI and global ocean temperature and their phase differences are given on Fig. 3(6).

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