"Physics of Auroral Phenomena", Proc. XLVII Annual Seminar, Apatity, pp. 101-104, 2024

Polar Geophysical Institute

DOI: 10.51981/2588-0039.2024.47.021

ANALYSIS OF THE RELATIONSHIP BETWEEN SOLAR ACTIVITY AND TEMPERATURE CHANGES IN THE CONSTANT TEMPERATURE ZONE OF UHLOVITSA CAVE AND THE CITY OF SMOLYAN, BULGARIA

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Abstract. The study presents an investigation of the impact of the solar activity on the temperature regime of the cave atmosphere in the zone of constant temperatures in the Uhlovitsa karst cave, located in the central part of the Rhodope Mountains. The course of the ground-level atmospheric temperature in Smolyan, a city located closest to the cave entrance, has also been studied. For the work, databases for the temperatures in the cave and in Smolyan, and solar activity indices from public databases for the number of sunspots (Sn), the total solar irradiance (TSI), and the solar radio emission F10.7) have been used for the period 1968 – 2022. The analysis of the temperature regimes in the specific underground environment and the area adjacent to the cave shows significant correlations between the solar activity and the temperature regime in Uhlovitsa cave. The study is an attempt to establish links and a physical understanding of the complex interactions between solar activity and the ground-level atmosphere.

Introduction

The study of temperature conditions in caves is of crucial importance in paleoclimatic scientific research, as it was highlighted by *Domínguez-Villar et al.* [2013]. Such research encompasses a broad range of aspects, including detailed monitoring of daily, monthly, and annual temperature variations [*Sanderson et al.*, 2002], and the analysis of temperature differences based on altitude [*Drăgușin et al.*, 2019]. Understanding the role of airflow and ventilation in the climatic conditions of caves is also of paramount importance [*De Freitas et al.*, 1987].

Furthermore, an important aspect of these studies is examining the mechanisms by which changes in surface atmospheric temperature are reflected in the cave microclimate. This helps in assessing whether caves mirror the global warming trend [*Domínguez-Villar et al.*, 2015; *Badino*, 2004]. Studies of small and relatively isolated cave systems are critical for understanding the mechanisms governing temperature variations in these environments [*Liu et al.*, 2017].

Stoeva et al. [2006] explore another significant element in the study of cave climate: the influence of short-term and long-term changes in solar activity, which manifest even in the stable microclimate of karst caves. These studies underscore the importance of solar activity for climate patterns in cave environments [*Stoev et al.*, 2019].

Uhlovitsa Cave, located in the Rhodope Mountains near the town of Smolyan, at geographical coordinates 41° 34′ 40″ north latitude and 24° 41′ 40″ east longitude, is a geological site of exceptional interest. The entrance to the cave is situated at an approximate elevation of 1040 meters above sea level.

Data Used

In the present study, annual average temperature values for the period from 1968 to 2022 for the constant temperature zone of Uhlovitsa Cave have been used. These data were provided by the Bulgarian Tourist Union (BTU).

As indicators of the solar activity, annual average values of the sunspot numbers (Sn), the radio emission F10.7, and the Total Solar Irradiance (TSI) have been used. Information about Sn from 1968 to 2022 was obtained from the International Sunspot Number Service (SILSO) via the website: https://www.sidc.be/SILSO.

The values of radio emission F10.7 have been provided by the Laboratory for Atmospheric and Space Physics at the University of Colorado, accessible through their website https://lasp.colorado.edu/lisird/data/noaa_radio_flux. The study includes annual average values of radio emission F10.7 for the period from 1968 to 2018.

Data for Total Solar Irradiance (TSI) are available on the website of the National Center for Environmental Information (NCEI) of NOAA. We use the annual average values for the period from 1968 to 2022, available at the following address: https://www.ncei.noaa.gov/data/total-solar-irradiance/access/yearly/.

The data concerning the average surface air temperature (annual average value) for the town of Smolyan for the period 1968-2020 were obtained on January 25, 2024, from: https://climateknowledgeportal.worldbank.org/country/bulgaria/trends-variability-historical.

Data Processing Methods

Various statistical and analytical data processing methods were applied within this scientific study. Initially, a comprehensive graph was created to visualize the temporal dynamics of the examined parameters—temperature, radio emission F10.7, total solar irradiance (TSI), and the sunspot numbers (S_n), tracking their changes over time.

A statistical analysis was conducted to evaluate the correlation between temperatures in the constant temperature zone (TUhl) and Sn, TSI, and F10.7. The Pearson correlation coefficient (r) is a statistical indicator that measures the strength and direction of the linear relationship between two variables. The standard error of the correlation coefficient (S_r) provides an estimate of the accuracy of the correlation coefficient r, and the values of the t-statistic are used to test the statistical significance of the Pearson correlation coefficient.

Fourier analysis allows the examination of periodic fluctuations and patterns in time series. This method provides detailed information and contributes to understanding the complex interactions within the climate system and their potential impact on Earth processes.

Results

A comparison between the temperature trends in the city of Smolyan and Uhlovitsa Cave reveals interesting differences. Temperatures in Smolyan are characterized by significant variability and a general upward trend over the study period, while the values in Uhlovitsa Cave remain considerably more stable. This stability highlights the cave environment's ability to insulate itself against external atmospheric influences.

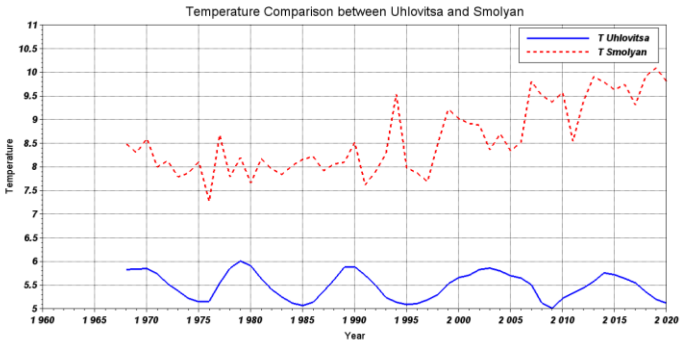

Figure 1. Amplitudes of the maximum and minimum temperatures measured in Uhlovitsa Cave and Smolyan.

Table 1 presents correlation coefficients 0.744 for Sn/T_{Uhl}, 0.692 for TSI/T_{Uhl}, and 0.719 for F10.7/T_{Uhl}, indicating a strong positive correlation between these astrophysical and temperature parameters.

The standard error of the correlation coefficient

$$S_r = \sqrt{\frac{1-r^2}{n-2}},$$

where r is the Pearson correlation coefficient, and n is the number of observations. For the three analyzed relationships, the standard errors were calculated to be approximately 0.092, 0.099, and 0.095, respectively, indicating moderate accuracy of the correlation coefficients.

The t-statistic values

$$t = \frac{r}{S_r}$$

for each correlation are sufficiently high (8.11 for Sn/TUhl, 6.98 for TSI/T_{Uhl}, and 7.53 for F10.7/TUhl), suggesting that the correlations are statistically significant and the likelihood of the correlation being a random occurrence is low. This supports the hypothesis of a strong relationship between the cave temperatures and the parameters

$$S_r \times 2.01(T_{\text{crit}} = 2.01).$$

We can expect the true value of r to fall with a 95% confidence in the interval r ± Sr *t_{crit}, with t_{crit}=t(α_{crit},df), where t ist he value oft the Student‘s distribution, for the two side test the critical significance level α = 1 – p = 0.05 and the degree of freedom df=n-2, in our case that means df=53. The critica t-value is obtained to be about 2.01.

For Sn/T_{Uhl}, the interval is 0.744 ± 0.184, or TSI/T_{Uhl} it is 0.692 ± 0.199, and for F10.7/T_{Uhl} it is 0.719 ± 0.190, allowing for the estimation of r values with a higher degree of confidence (Table 1).

Spectral Analysis of F10.7, Sunspot Number (Sn), and TSI

The analysis of Sn (Fig. 2a) reveals a distinct peak at periods around 10-12 years, corresponding to the characteristic period of the solar cycle. Similarly, the graph for F10.7 (Fig. 2b) also shows a pronounced peak in the same range, with F10.7 (radio emission at a 10.7 cm wavelength) serving as a proxy for solar activity. Sunspots are direct indicators of solar activity, further confirming the synchronization of these measurements with the solar cycle. Additionally, the TSI graph (Fig. 2c) shows increased amplitude within the same period range, suggesting that variations in TSI may also be influenced by the solar cycle.

Table1. Pearson's correlation coefficient r.

	Person's correlation coefficient r	**Sr**	**t**	**r±Sr*2.01 (T_{crit} = 2.01)**
Person's correlation coefficient r S_n/T_{Uhl}	0.744	0.092	8.11	0.744 ± 0.184
Person's correlation coefficient r TSI/T_{Uhl}	0.692	0.099	6.98	0.692 ± 0.199
Person's correlation coefficient r $F10.7/T_{Uhl}$	0.719	0.095	7.53	0.719 ± 0.190

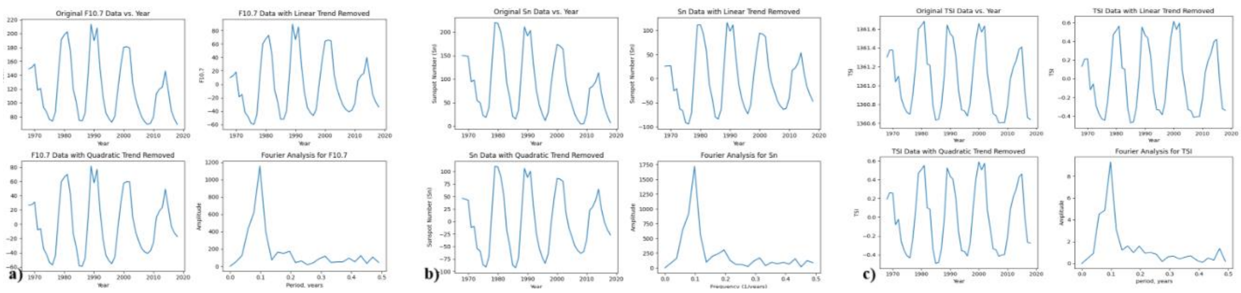

Figure 2. Original Data vs. Year, Data with Linear Trend Removed, Data with Quadratic Trend Removed, Amplitude spectrum.

In the spectral analysis of the temperature data for Smolyan (Fig. 3), we observe a pronounced peak with a magnitude around 7.5 years. There is no clear peak within the 11-year range, but there is an indication of increased amplitude over longer periods. This might suggest that although temperature variations are related to the solar cycle, they could also be influenced by other factors and interactions that are more complex and not directly synchronized with the 11-year solar cycle.

The spectral analysis of the temperature data for Uhlovitsa (Fig. 4) shows a clearly pronounced significant peak associated with the 11-year solar cycle.

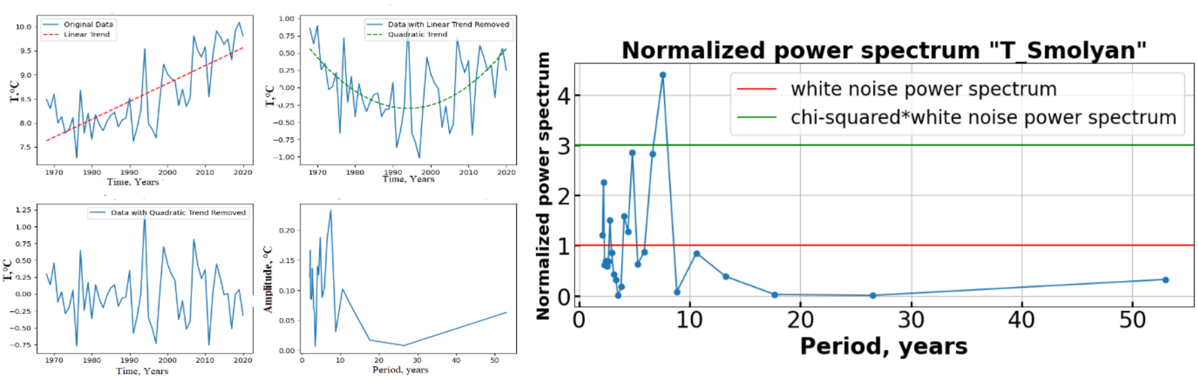

Figure 3. Original Data vs. Year, Data with Linear Trend Removed, Amplitude spectrum, Normalized power spectrum.

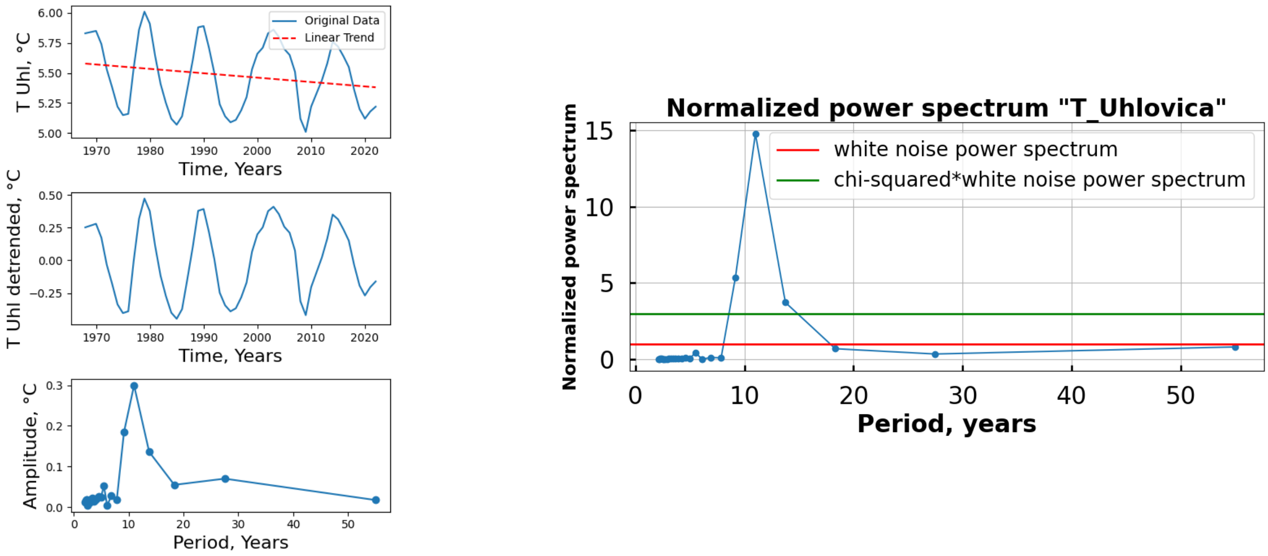

Figure 4. Original Data vs. Year, Data with Linear Trend Removed, Amplitude spectrum, Normalized power spectrum.

Conclusions

The present study of temperatures in the constant temperature zone of Uhlovitsa Cave and their associated solar parameters reveals significant correlation coefficients, highlighting the close relationship between solar activity and climatic conditions in the cave environment. The spectral analysis of surface air temperature in the Smolyan region shows a clearly pronounced and statistically significant peak around 7.5 years, likely reflecting the influence of the North Atlantic Oscillation on surface temperature. On the other hand, the temperature records from Uhlovitsa Cave show a distinct and significant peak around 11 years, corresponding to the 11-year solar cycle, emphasizing the potential impact of solar activity on cave temperatures.

The discovery of a pronounced 11-year cycle in the temperatures of Uhlovitsa Cave lays the groundwork for further research that could clarify the reasons behind this apparent correlation. Long-term meteorological observations at various locations within the cave are necessary to provide additional evidence and help deepen our understanding of the interactions between solar activity and climatic conditions in the subterranean world. This research lays the foundation for future scientific developments in paleoclimatology and geology, promising intriguing discoveries for the future.

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