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Correlation between Solar Activity and Lightning Storms in the City of São Paulo.

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Abstract Summary

This study investigates the relationship between solar activity and atmospheric electrical phenomena by analyzing time series of sunspots and lightning storms in São Paulo from 1958 to 2021. Statistical pre-processing and time series decomposition were applied to identify trends and seasonal behavior. To assess temporal-frequency patterns, the Continuous Wavelet Transform was employed, focusing on Morlet wavelets. Results show that both sunspots and lightning storms exhibit cycles between 8 and 16 years, with particular alignment to the 11-year solar cycle. Wavelet coherence analysis revealed a dynamic correlation: antifase behavior prevailed until the 1980s, shifting to in-phase from the 1990s onward. This shift suggests a modulation of thunderstorm activity by solar phenomena, possibly intensified by the South Atlantic Magnetic Anomaly (SAMA). These findings reinforce the role of solar activity as a secondary modulator of atmospheric phenomena under specific local conditions.

Introduction

When solar winds interact with Earth's magnetosphere, they can cause disturbances and changes in the system's energy balance, which may potentially influence the occurrence of electrical storms. The geomagnetic index is used to quantitatively monitor the electromagnetic activity associated with variations in Earth's magnetic field. Time series analyses were conducted and discussed for lightning storm and sunspot data, covering the period from 1958 to 2021 in the city of São Paulo, Brazil. The statistical treatment of the time series involved trend removal, seasonal adjustment, and data normalization. To identify cyclical patterns, Wavelet Transforms were applied. Subsequently, cross-wavelet analysis was performed to determine the degree of correlation between the two series and to assess the influence of sunspots on the occurrence of electrical discharges.

For data processing, Python libraries specialized in time series analysis and statistical treatment were used. The Wavelet Transform of the sunspot series revealed a periodicity of approximately 11 years, representing the well-known solar cycle. The interval with the greatest intensity (reddest region) was observed between 1970 and 2000, suggesting a climatic variation in lightning storms with a periodicity between 4 and 16 years. This periodicity is close to the 11-year solar cycle, indicating a possible relationship between solar activity and electrical storms.

The direction of the arrows in the cross-wavelet analysis suggests variations in time lag, which may indicate delayed responses of electrical storms to solar activity. The time series analysis revealed a strong periodicity between 4 and 16 years, with emphasis on the 11-year cycle, possibly linked to the solar cycle. The correlation between sunspots and lightning storms was more evident between 1970 and 2000, pointing to an influence of solar activity. However, after 2010, this relationship became less significant, possibly due to climate changes. These results indicate that the Sun may influence the occurrence of electrical storms, although other factors should also be considered.

Method and Theory

This study aimed to analyze the correlation between solar and atmospheric variables through time series. Datasets of lightning storms, sunspots, galactic cosmic rays, and geomagnetic indices were used. The data were collected from reliable sources such as IAG-USP, SILSO, and NMDB.

A statistical pre-processing was performed, which included time series decomposition to remove trends and seasonality, as well as data normalization. To identify cyclical patterns and temporal variations in the data, the Continuous Wavelet Transform (CWT) was applied using the Morlet wavelet function. This technique allowed for the analysis of the frequency content of the signals over time, enabling the detection of dominant cycles.

Additionally, cross-wavelet (Wavelet Coherency) analysis was applied to examine correlations between variable pairs, particularly between lightning storms and sunspots. This approach made it possible to detect periods of phase and anti-phase between the signals.

Data processing was carried out using RStudio and Jupyter Notebook (Python), with the aid of libraries such as WaveletComp, numpy, pandas, and matplotlib. RStudio was essential for decomposing the signals and performing trend and seasonality analysis. Time series with higher temporal regularity underwent anomaly removal, while the others were only normalized.

All data were organized, processed, and analyzed following standard time series protocols, ensuring robust and reproducible results.

Results

The analysis revealed a complex and temporally variable relationship between the number of sunspots and the occurrence of lightning storms in the city of São Paulo between 1958 and 2021. Initially, linear regression analysis did not show statistically significant correlation between these variables, indicating a non-linear relationship. Therefore, the Wavelet Transform was applied, as it is more suitable for analyzing non-stationary time series and detecting correlations across multiple time scales.

From the decomposition of the lightning storm time series, clear seasonality was observed, with peaks during the summer months (December, January, and February), strongly linked to the South Atlantic Convergence Zone (SACZ). The sunspot series, in turn, revealed the well-known 11-year *Schwabe* cycle, with marked variations in solar activity over time.

The wavelet analysis showed that the lightning storm series presents periodicities similar to the solar cycle, particularly in the 8–16 year range, suggesting that solar activity influences the variability of these events. The power spectra indicated greater alignment during the summer months, a period of increased atmospheric instability.

The wavelet coherence analysis between the two variables revealed a dynamic behavior: until the mid-1980s, the relationship was predominantly anti-phase — that is, periods of high solar activity corresponded with fewer lightning storms. From the 1990s onward, the relationship shifted to being predominantly in-phase, with both series rising and falling together. This change may reflect alterations in the coupling mechanisms between space weather and the Earth's atmosphere, or increased local sensitivity due to urbanization and pollution.

Moreover, the presence of the South Atlantic Magnetic Anomaly (SAMA), which weakens geomagnetic protection in the Southeast region of Brazil, may have amplified the effects of solar activity in São Paulo, enhancing solar modulation of atmospheric electrical events.

These findings indicate that, although the relationship between sunspots and lightning storms is not constant over time, there is evidence that the solar cycle acts as a secondary modulator of atmospheric electrical activity, particularly during solar maxima and under favorable local meteorological conditions.

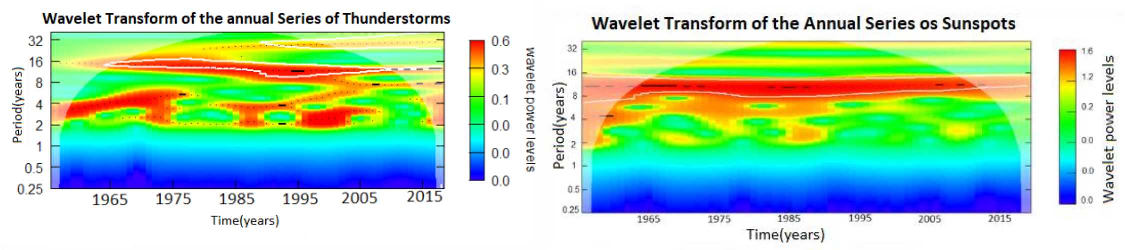

Figure 1: *Continuous Wavelet Transform* of the time series of Lightning Storms and Sunspots. The results show an ~11-year and a ~4-year cycle in the lightning storm data (left image), and a clear ~11-year cycle in the sunspot series (right image), representing the known 11-year solar cycle.

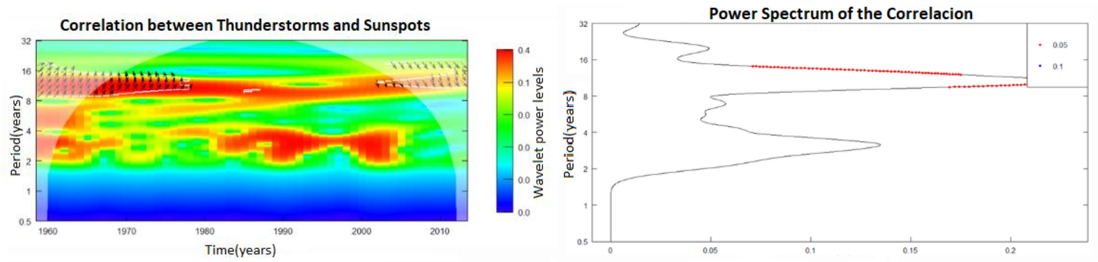

Figure 2: *Cross-wavelet coherence* between the lightning storm and sunspot time series. The arrows indicate the phase relationship: rightward arrows represent in-phase behavior, while leftward arrows indicate anti-phase behavior. The power spectrum shows which cycles are active and how intense they are over time.

The Wavelet Transform of the sunspot series reveals a periodicity of approximately 11 years, corresponding to the solar cycle. The strongest period (redest region) occurs roughly between 1970 and 2000, suggesting a climatic variation in lightning storms with periodicities ranging from 4 to 16 years. The direction of the arrows indicates phase lag variations over time, which may reflect delayed responses of lightning storms to sunspot activity.

Conclusions

This study concludes that solar activity, primarily represented by the 11-year sunspot cycle, acts as an important climatic modulator, directly influencing the variability of atmospheric phenomena such as lightning storms. The application of advanced time series analysis techniques, such as the wavelet transform, made it possible to dynamically identify this relationship over time.

The analyses showed that the correlation between sunspots and lightning storms is not constant, but rather variable. Until the mid-1980s, the relationship was predominantly anti-phase — that is, periods of high solar activity coincided with a lower number of storms. From the 1990s onward, this pattern shifted to in-phase behavior, suggesting that solar activity and lightning storm frequency began to rise and fall together.

This change may be associated with local factors such as increased urbanization, rising air pollution, and the influence of the South Atlantic Magnetic Anomaly (SAMA), which makes the atmosphere over southeastern Brazil more vulnerable to the penetration of energetic particles. These factors may have contributed to greater atmospheric sensitivity to solar activity.

In addition, summer was confirmed as the season with the highest incidence of lightning storms, reinforcing the idea that solar influence acts in combination with local seasonal and meteorological patterns.

Therefore, although solar activity alone does not fully determine the occurrence of lightning storms, it appears to function as an important modulator, especially when combined with favorable atmospheric conditions. The results underscore the importance of interdisciplinary studies between space weather and terrestrial meteorology, and highlight the need for joint analysis of these variables to better understand the complexity of atmospheric processes in the São Paulo region.

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