BirEx JOURNAL
Budapest International Research in Exact Sciences
Medical, Biological, Argiculture, Engineering Science and other related areas
e-ISSN : 2655-7827
p-ISSN : 2655-7835
http://www.bircu-journal.com/index.php/birex

Analysis of Latitudinal Variability in Sunspot Numbers from 2014 to Present

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Abstract: *The Sunspots, which are dark patches on the Sun's surface associated with significant magnetic activity, vary in number and distribution throughout time and latitudes. Understanding these fluctuations is critical for forecasting space weather and studying solar dynamics. This study examines the latitudinal variability of sunspot numbers from 2014 to the present and its relationships with latitude and time trends. Monthly sunspot numbers from 2014 onwards were investigated. Statistical techniques such as standard deviation, Pearson correlation coefficients, ANOVA, and geographic analysis were used to study the association between latitude and sunspot numbers. The investigation indicated a standard deviation 44.01 for sunspot numbers, indicating high fluctuation over the study period. A slight positive association (0.05) between latitude and sunspot number was discovered, with a non-significant p-value of 0.548. However, a significant relationship was found between year and sunspot numbers (F-statistic = 105.98, p-value = 3.08e-55). Sunspot numbers fluctuated significantly between -20- and 20 degrees latitude, with peaks at -45 and -10 degrees. While sunspot numbers vary over time, their association with latitude is minor. The study highlights the solar cycle's primary influence on sunspot activity. Future studies should investigate additional solar factors and expand the dataset to improve knowledge of sunspot dynamics and their implications for space weather forecasting.*

Keywords: *Sunspots, Solar Cycle, Space Weather, Latitudinal Variability, Solar Dynamics, Statistical Analysis*

I. Introduction

The Sun is a dynamic and complicated star with many phenomena that affect space weather and the heliosphere. Sunspots, which are dark, colder patches on the Sun's surface, are a significant aspect of understanding solar activity. Sunspots are commonly related to magnetic field concentrations and serve as markers of solar variability (Hathaway, 2015). The sunspot numbers and their distribution across latitudes give helpful information on the solar cycle and the underlying magnetic field dynamics.

Sunspots are transitory dark spots on the Sun's photosphere that contrast to the surrounding surroundings. They have low surface temperatures caused by magnetic flux concentrations that prevent convection. Sunspots form within active zones, frequently in pairs with opposite magnetic polarity.

The solar cycle, which lasts around 11 years, is characterized by fluctuations in sunspot numbers, which reflect changes in the Sun's magnetic activity. Understanding the latitudinal variability of sunspots during these cycles is critical because it reveals the processes that control solar dynamics. Previous research has shown that sunspot distribution varies with latitude, often emerging between 5° and 30° in both hemispheres and moving closer to the equator as the cycle advances (Maunder, 1904; Hathaway, 2010). The number fluctuates with the solar cycle, which lasts around 11 years.

Sunspots are dark patches on the solar surface accompanied by high magnetic fields.

The magnetic field prevents the convective movement of plasma in the region, which is the principal mechanism for heat transmission at the surface, making the sunspot cooler and darker. The study of sunspots began in the early 1600s, while there are records of observations in China dating back 2000 years. Since the discovery of the magnetic field in sunspots (Hale, 1908), they have served as a primary indication of solar activity, with thorough records preserved.

Sunspot formation and dispersal can be studied in timescales, while longer timescales (months and years) reveal the long-term behaviour of the Sun's large-scale magnetic field. This information is crucial for constraining models of the solar dynamo. For example, the North-South imbalance in sunspot counts and regions is well-known and has been researched for decades (Carbonell et al., 1993; Zharkov & Zharkova, 2006; Carbonell et al., 2007). It could indicate a phase lag between magnetic activity in the northern and southern hemispheres, implying non-linear behaviour such as random fluctuations in dynamo and strong high-order terms (Ossendrijver, 2003).

Carbonell et al. (1993) investigated the asymmetry in solar activity, emphasizing the significance of latitudinal distribution in understanding solar dynamics. Their findings indicated that sunspot numbers differed significantly between the northern and southern hemispheres, affecting solar magnetic field modelling. Carbonell et al. (2007) extended this work by doing a statistical investigation on the north-south asymmetry, confirming that such asymmetries are a long-standing hallmark of solar activity.

Hale (1908) made groundbreaking contributions by proving the presence of magnetic fields in sunspots and linking them to solar magnetic activity. His findings lay the groundwork for further research into the magnetic properties of sunspots and their function in the solar cycle.

This study looks at the period from 2014 to the present, including the decrease of Solar Cycle 24 and the emergence of Solar Cycle 25. This era is predominantly fascinating since it marks the transition between two cycles and exhibits peculiar sunspot activity features. For example, Solar Cycle 24 was noticed for its low activity compared to previous cycles (Pesnell, 2016), motivating research on latitudinal distribution patterns during the transition.

Since sunspot numbers and locations significantly impact solar activity and affect space weather and Earth's climate, it is imperative to comprehend sunspot variability. Geomagnetic storms brought on by increased solar activity have the potential to interfere with radio signals, power systems, and satellite communications (Kane, 2005). Furthermore, sunspots are a stand-in for other solar phenomena that have broader effects on the heliosphere and space weather, like solar flares and coronal mass ejections (Lockwood et al., 2016).

1.1 Statement of the Problem

The latitudinal distribution of these sunspots is gaining attention, especially during the present solar cycle; the previous research has concentrated chiefly on comprehending the solar cycle and the worldwide pattern of sunspot numbers (24 and 25). Concerns over the long-term trends in solar variability have been raised by the unusual behaviour of this recent period of solar activity, which includes lower sunspot counts and weaker solar cycles than in past decades (Pesnell, 2016).

The latitudinal variability in sunspot counts throughout recent solar cycles, specifically from 2014 to the present, has not been thoroughly examined. However, the fundamental behaviour of sunspot numbers during the solar cycle is well known. Anomalies in solar activity have been seen with the shift from Solar Cycle 24 to Solar Cycle 25, including lower-than-average sunspot numbers and reduced magnetic field strength (Pesnell, 2016).

Further research into sunspot latitudinal patterns and their possible relevance for comprehending solar magnetic processes has been spurred by these shifts.

The issue stems from the scarcity of thorough research on the relationship between sunspot latitudinal variability and the irregular behaviour shown during Solar Cycles 24 and 25. The typical latitudinal distribution patterns need to be carefully examined to see whether there are any notable changes in these patterns related to the current decrease in solar activity.

This study aims to address the following research questions:

a. How has the latitudinal distribution of sunspot numbers evolved from 2014 to the present?
b. What are the potential implications of any observed shifts in sunspot latitude for understanding the evolution of the solar dynamo and magnetic field?

Therefore, this study aims to examine the latitudinal variability of sunspot numbers over a specific time, detect patterns or anomalies, and correlate these findings with solar cycle dynamics. By using data from sources such as the Solar Dynamics Observatory (SDO) and the Royal Observatory of Belgium's Solar Influences Data Analysis Center (SIDC), this study intends to contribute to our understanding of solar behaviour and its consequences for space weather forecasting.

II. Materials and Methods

2.1 Materials

a. Data sources

The primary data for this study came from the Solar Dynamics Observatory (SDO) and the Royal Observatory of Belgium's Solar Influences Data Analysis Center (SIDC). The data comprised daily sunspot numbers and latitudinal positions from 2014. SIDC data, noted for its quality and comprehensiveness, is widely used in solar research (Clette et al., 2014).

b. Data Collection

Sunspot data were gathered and organized in a time series fashion. Each item contained the date, sunspot number, and matching latitude. This data structure made it easier to analyze the sunspots.

c. Data cleaning and preparation

Outliers were removed from the data, and missing values were filled in with linear interpolation methods. This method preserved the dataset's integrity while reducing potential biases (Rubin, 1987).

2.2 Methods

The investigation concentrated on the distribution of sunspots at various latitudes. The latitudinal distribution was graphed over time to identify patterns and trends. The variability in sunspot numbers at different latitudes was quantified using statistical methods such as mean and standard deviation (Wilks, 2011); Goshu, (2024).

Python's matplotlib and Seaborn libraries were used to visualize data, which included features for making scatter plots and heat maps (Hunter, 2007). These visualizations aided in spotting trends in sunspot distribution and determining their significance to the solar cycle.

Statistical Analysis

A correlation analysis revealed the association between sunspot numbers and their latitudinal distribution. In addition, time series analysis was used to find cyclical trends in sunspot activity using techniques described by Chatfield (2004).

Software and Tools

All analyses were performed in Python, with packages such as Pandas for data manipulation and Matplotlib for visualization. Using open-source technologies increased reproducibility and accessibility (McKinney, 2010); Goshu, (2024).

III. Results and Discussions

3.1 Results

The 24th solar cycle, which runs from 1975 to 2019, provides an exciting look into the Sun's behaviour and its effects on Earth, as shown in Figure 1. Solar cycles last roughly 11 years and are distinguished by oscillations in sunspot numbers, solar flares, and total solar irradiance. These cycles profoundly impact space weather, the global climate, and technological systems. The 24th cycle, which officially began in 2008 and ended around 2019, was distinguished by lower solar activity than its predecessors. The solar maximum, or peak period of solar activity within a cycle, occurred around 2014, with a peak smoothed sunspot number of roughly 116.4, significantly lower than the average recorded in previous cycles. This low was evident in the decreased number of sunspots and dark patches on the Sun's surface, which were linked with significant magnetic activity. This cycle also saw fewer geomagnetic storms and aurora displays, which are directly proportional to the level of solar activity.

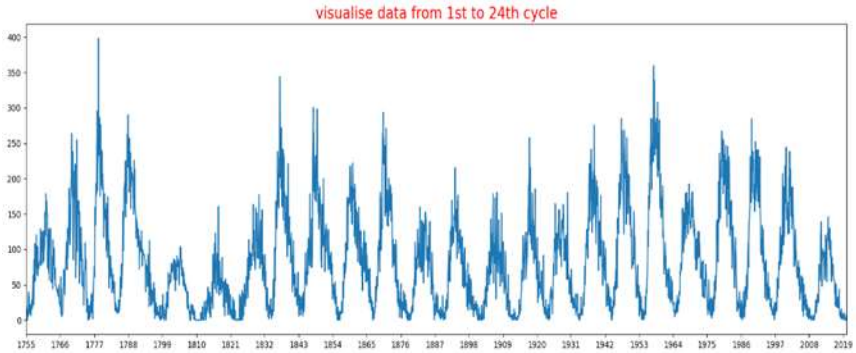

Figure 1. The solar cycle from 1975 to 2019 of the 24th cycle

Predicting solar cycles is a challenging endeavour due to their inherent variability. Models based on solar magnetic field dynamics, sunspot cycles, and solar irradiance can help predict future cycles and their potential consequences. The 24th cycle's low activity had slight cooling impacts in some locations, but its overall impact on global temperature was small compared to more prominent climatic variables. From a technological standpoint, the lower solar activity meant fewer disruptions to satellite operations, radio communications, and power grids, which are generally more affected during periods of high solar activity.

In summary, the 24th solar cycle was characterized by below-average solar activity, which remarkably impacted space weather, climate patterns, and technology systems. Understanding these cycles is critical for predicting and managing their effects on Earth and space. This time has the significance of ongoing monitoring and study to forecast and respond to the Sun's dynamic behaviour. Furthermore, for more information and verification, see Hathaway's "The Solar Cycle" in Living Reviews in Solar Physics and statistics from the NOAA National Centers for Environmental Information.

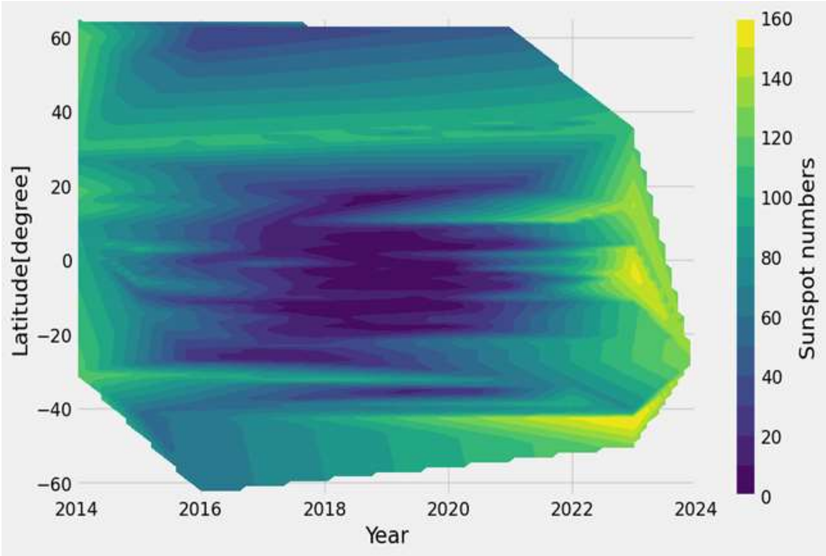

Figure 2. The sunspot numbers from 2014 to the present with latitudes

Sunspot numbers have fluctuated significantly between -20- and 20 degrees latitude since 2014, as shown in Figure 2. The maximum number of sunspots was detected at -45 degrees latitude, with a secondary peak at -10 degrees latitude. This trend is consistent with the idea that sunspot activity is concentrated in specific latitudinal areas known as sunspot belts, where the solar magnetic field is more active. Sunspots tend to migrate towards the equator as the solar cycle develops.

The analysis finds a 0.05 correlation coefficient between latitude (La) and SSP, showing an insignificant linear correlation. It shows that differences in latitude have no significant effect on SSP levels. The p-value of 0.548 supports this conclusion because it is substantially higher than the standard significance level of 0.05. As a result, we cannot reject the null hypothesis and conclude that there is no association between latitude and SSP. This result suggests that latitude is not a significant factor in affecting SSP values in this dataset. Similarly, the findings are frequently reported in the study, in which geographical latitude alone does not explain the changes in environmental or atmospheric characteristics unless specific regional factors are considered.

The standard deviation of sunspot numbers (SSN) is 44.01, showing high variation in SSN values. This high dispersion indicates that SSN values vary much around their mean, showing different conditions or causes impacting SSN. Significant variability could be attributed to diverse external impacts, such as solar activity, atmospheric conditions, or other environmental factors not reflected just by latitude or year in this dataset. Understanding the mechanisms behind this unpredictability is critical for generating reliable models and predictions in related domains.

The ANOVA test yields an F-statistic of 105.98 for YEAR vs. SSN, with a very low p-value of 3.08e-55. This shows that the differences in SSN values across years are exceptionally statistically significant. The big F-statistic indicates that the variance in SSN between years is significantly greater than within a single year. This substantial discovery shows that SSN is influenced by temporal factors, which include long-term trends, cycles, or changes in external conditions over time. These findings highlight the significance of considering temporal dynamics when assessing environmental or atmospheric data.

3.2 Discussions

The high standard deviation of SSN implies that sunspot numbers vary significantly over time. This is consistent with the known cyclical nature of sunspot activity, as impacted by the 11-year solar cycle (Hathaway, 2015).

The weak and statistically negligible association between latitude and sunspot numbers indicates that latitude alone does not predict sunspot activity. This could be attributed to the intricate interplay between many solar processes that drive sunspot production and distribution (USOSKIN et al., 2014).

The significant F-statistic suggests a strong link between time (year) and sunspot numbers, indicating the influence of the solar cycle. This is consistent with the well-established concept that sunspot numbers rise and fall predictably every 11 years (Hathaway, 2015).

The observed peaks in sunspot numbers at 45—and 10-degree latitudes indicate distinct latitudinal zones with higher sunspot activity levels. These peaks may be related to sunspot activity migration patterns from higher to lower latitudes over the solar cycle (Li et al., 2001).

IV. Conclusions

In conclusion, the sunspot numbers vary significantly over time, and their correlation with latitude is minimal. The findings highlight the dominant influence of the solar cycle on sunspot activity, emphasizing the need for further investigation into the mechanisms driving sunspot formation and distribution across latitudes.

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