The Effect of Sunspot Activity on Earth's Extreme Climate

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Abstract: The eastern equatorial Pacific Ocean experiences an oscillation of winds and sea surface temperatures known as the El Nino-Southern Oscillation (ENSO), which is the most significant signal of inter-annual change in the global climate system. This low-latitude air-sea interaction, manifested in the Southern Oscillation in the atmosphere and the El Nino-La Nina transition in the ocean, has a profound impact on global weather patterns. As an important indicator of solar activity, sunspot activity is closely related to the Earth's climate system and may modulate ENSO events through various ways. The mechanism of sunspot activity affecting ENSO is discussed in this paper. First, the effects of sunspots on the sun, Earth's climate and ENSO are analyzed. In addition, the correlation between the number of sunspots and ONI was also analyzed, further revealing the existence and correlation of this effect. The results are helpful to further understand the formation and development mechanism of ENSO, and provide a new theoretical basis for improving the accuracy of ENSO event prediction.

1 INTRODUCTION

At a distance of about 150 million kilometers, the Sun is the closest star to Earth. The Sun continuously emits 3.8×10^{26} joules/second of energy through hydrogen fusion in its core, of which about 1.7×10^{17} joules/second reaches the Earth, constituting 99.98% of the total energy received at the surface. Solar activity can be divided into quiet periods and active periods, which mainly include sunspots, flares, solar prominences and coronal mass ejections. In the eastern equatorial Pacific Ocean, there is a wind field and sea surface temperature oscillation known as ENSO (El Nino Southern Oscillation). The Southern Oscillation in the sky and the ENSO transition in the ocean serve as indicators of the low-latitude air-sea interaction known as ENSO. Its formation and development are the result of the interaction of many factors, including the interaction between the ocean and the atmosphere, the change of trade wind direction, the change of sea surface temperature, the difference of atmospheric pressure, Walker circulation, Earth rotation and global climate change. Many studies have shown that the Earth's extreme climate is closely related to solar activity. In view of this, this paper aims to explore the correlation between sunspot activity and ENSO. The aim is to deepen our understanding of the formation mechanism of these extreme climates and provide scientific basis for understanding and predicting ENSO events.

1.1 Composition and Structure of the Sun

The Sun is composed mainly of hydrogen and helium, and these two elements make up the majority of the Sun's total mass. Among other elements, it also contains carbon, oxygen, neon, and iron. Although there is no obvious barrier between the internal material, which is primarily plasma, its density drops exponentially with increasing altitude above the photosphere. For ease, the solar radius is frequently calculated using the distance between the sun's visible surface and core (Den, 2023). Nuclear fusion occurs all the time in the sun, and energy is diffused from the inside to the outside. In this process, high-energy particles such as gamma rays and neutrinos generated by nuclear fusion will gradually decay into photons of lower energy such as ultraviolet, visible light and infrared light.

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The current research believes that the solar structure is mainly divided into five layers, namely core, radiation zone, convection zone, photosphere and corona. Common solar activities mainly include sunspots, flares, solar prominences, coronal mass ejections, etc. These activities will have a certain impact on space communications, power systems, satellite operations, climate and so on.

1.2 Sunspot

Sunspots are a feature on the surface of the Sun, proposed by Rudolf Wolf, usually located in the photosphere and are the result of the upward push of the intense magnetic flux inside the sun. Along this flux, heat is heated in the upper photosphere and chromosphere regions, usually in the form of light spots and blotches--often referred to as active regions (NOAA, 2025). These active areas are typically where solar eruptions like solar flares and coronal mass ejections occur. To ascertain and forecast the solar cycle's advancement and, eventually, solar activity, several organizations, like NASA and NOAA, monitor sunspots (NASA, 2025).

The solar cycle is about 11 years, and the total number of sunspots varies throughout the cycle. According to the different number of sunspots can be divided into solar minimum and solar maximum. The former is characterized by a low number of sunspots, while the latter is characterized by a high number of sunspots. Sunspots can be used as a solar activity indicator and as a possible source of violent solar activity, including coronal mass ejections and flares. Furthermore, the temperature of Earth may be impacted by solar activity in the long run.

1.3 ENSO Phenomenon

ENSO is a wind field and sea surface temperature oscillation that occurs in the eastern equatorial Pacific Ocean. ENSO is a low-latitude sea-air interaction phenomena that is indicated by the Southern Oscillation in the atmosphere and the El Nino-La Nina transition in the ocean (Kessler, 2002). In the Pacific Ocean close to the equator, the east has a low temperature and the west a high one. The air in the western Pacific Ocean is warm and humid, prevailing updraft, becoming an area with extremely vigorous convective activity, and also the most abundant precipitation in the Pacific Ocean, while the eastern Pacific Ocean is cold water, cold water makes the air above it cool and dense, prevailing downdraft on the ocean surface, more sunny and less cloudy weather. This zonal circulation that flows east-west over the low-latitude Pacific Ocean is called the Walker circulation.

El Nino and La Nina are the two opposite phases of ENSO, which exhibit different characteristics in terms of the ocean and atmosphere. During El Nino, the eastward expansion of warm surface water causes the convection zone in the western tropical Pacific to drift eastward. This resulted in increased rainfall, decreased surface pressure and weakened trade winds in the eastern Tropical Pacific, while west of the date line, decreased rainfall and increased surface pressure. At the same time, this phenomenon will also cause and increase the global temperature abnormally (Philander, 1989). However, La Nina happens when the equatorial Pacific's exceptionally powerful trade winds push more warm water westward. It led to exceptionally low SST in the equatorial Middle Eastern Pacific Ocean, lower SST in the east, and higher SST in the west. El Nino has the opposite impact. This phenomenon will have a serious impact, which may lead to a significant reduction in agricultural production, and dry conditions also face increased fire, which affects agricultural forest planting and water supply reduction (ESCAP and Warning,2016).

ENSO is a significant natural climate event that, when combined, form a complex climate system that alternately manifests and exhibits periodic oscillations with a duration of roughly three to seven years. The primary driving force behind the complicated processes of ENSO creation is the interplay between the ocean and atmosphere. Southeast trade winds are often blown from east to west from the equatorial Middle Eastern Pacific. The western Pacific experiences warmer seas as a result of these winds pushing warm water toward it, while the eastern Pacific has cooler waters. When an El Nino occurs, the winds weaken or even reverse, which causes warm water to migrate from the western to the eastern Pacific. Second, shifts in the ocean's circulation are also significant determinants. Walker circulation keeps the western Pacific Ocean's warm, humid air ascending and the eastern Pacific Ocean's cool water upwelling. Walker circulation deteriorates during an El Nino, which reduces cold water upwelling in the Eastern Pacific Ocean and exacerbates the rise in SST.

2 ANALYSIS OF THE RELATIONSHIP BETWEEN SUNSPOT ACTIVITY AND ENSO

2.1 Influence of Sunspot Activity on the Sun

One of the most significant indicators of solar activity are sunspots, which are frequently associated with violent phenomena like solar flares and coronal mass ejections, which release massive amounts of electromagnetic radiation and high-energy particles into space, creating the solar wind. If sunspot activity is high, solar radiation is increased, and if it is low, solar radiation is diminished.

The formation of sunspots has a lot to do with the sun's magnetic field. The Sun's magnetic field is not evenly distributed, but can become extremely strong in certain regions. These strong magnetic fields inhibit the movement of the gas, which causes the temperature in these places to cool down and form sunspots.

2.2 Effects of Sunspot Activity on Earth's Climate

Solar flares and coronal mass ejections (CMES), which are common during sunspot activity, unleash massive volumes of plasma and high-energy particles towards Earth, creating the solar wind. Geomagnetic storms are the result of interactions between the solar wind and Earth's magnetic field. Changes in the Earth's magnetic field during geomagnetic storms can change air circulation patterns, which can have an impact on the climate system (Hathaway,2015).

There is a long-term relationship between sunspot activity and Earth's climate. During periods of low sunspot activity, Earth experienced a relatively cold period known as the "Little Ice Age." During this period, the earth's temperature dropped significantly, rivers froze, and crop yields decreased.

The effect of sunspots on Earth's climate is multifaceted, but this effect is relatively small and complex. Sunspot activity indirectly affects the Earth's climate system by changing the intensity of solar radiation, ultraviolet radiation, solar wind and geomagnetic activity.

2.3 Effects of Sunspot Activity on ENSO

The core driving mechanism of ENSO is the variation of the southeast trade winds in the equatorial Middle East Pacific. Peak sunspot activity's enhanced radiation alters the atmospheric pressure gradient and heats the equatorial atmosphere, weakening trade winds and encouraging the flow of warm water eastward, which leads to El Nino. Conversely, periods of low sunspot activity can lead to stronger trade winds, pushing more warm water to pile up in the western Pacific and intensifying cold water upturning in the eastern Pacific, creating a La Nina.

There is a periodic relationship between sunspot activity and ENSO. Sunspot activity has a cycle of about 11 years, while ENSO phenomena typically have a cycle of 2-7 years. It has been found that the peak and trough years of sunspot activity have significant effects on the intensity and frequency of ENSO. During peak sunspot years, El Nino may strengthen, while La Nina may weaken; Conversely, in sunspot valley years, El Nino events may weaken and La Nina events may strengthen.

3 SUNSPOT ACTIVITY AND ENSO DATA ANALYSIS

3.1 Source of Data on Sunspot Numbers

Sunspot Index and Long-term Solar Observations (SILSO) is an important project of the Royal Observatory of Belgium (ROB), Its history can be traced back to the sunspot observation network established by Rudolf Wolf at the Zurich Observatory in 1849(Clette,Svalgaard,Vaquero and Cliver,2014). Early data collection relied primarily on visual observations by observatories and amateur observers worldwide, and calculated daily indices based on the Wolff number formula:

$$W = k\left(10g + s\right)W = k\left(10g + s\right) \qquad (1)$$

In the early 20th century, due to data discontinuity caused by insufficient coverage of observation network, the predecessor institution of SILSO used interpolation method and analogy method of activity intensity of adjacent periods to fill the gap in data (Cliver and Ling, 2016).

Modern data acquisition system integrates multi-source observation technology. Since 1995, the

Michelson Doppler Imager (MDI) of the SOHO satellite and the Helioseismic and Magnetic Imager (HMI) of the SDO satellite have provided surface and white light images 24 hours a day. To help correct the weather disturbance error of ground-based observation. SILSO also uses a dynamic cross-calibration process to re-evaluate historical data using modern high-resolution data.

Therefore, SILSO has built a relatively complete database for recording sunspots. This paper takes it as a reliable data source, and visualizes and analyzes the public data in it. The data source is (Royal Observatory of Belgium, 2025).

3.2 Source of Data for Oceanic Nino Index (ONI)

Sea Surface Temperature (SST) refers to the temperature of the ocean surface, usually the water temperature of the ocean surface (usually within 0.5 m depth). SST data is a very important basic data in oceanography and climatology, widely used in weather forecast, climate research, Marine ecosystem research, fishery management and other fields. The source of SST data is mainly obtained through satellite remote sensing technology. The sensor on the satellite measures the radiation temperature of the ocean surface, and then inverts the SST.

The Nino 3.4 index is calculated based on the SST anomalies for the region of Nino 3.4 (5° N-5° S, 120° W-170° W), subtracted from each month's SST anomalies, which are usually based on 30-year climate averages. The calculation formula is as follows:

$$SST\ Exception = SST_n - \overline{SST_n} \quad (2)$$

Where: SST_n is SST value of this month;
$\overline{SSTn}$ is Revised monthly long term average SST;

The Oceanic Nino Index (ONI) is calculated using the three-month sliding average of the SST anomalies in the Nino 3.4 zone. The calculation formula is as follows:

$$Current\ Month\ ONI = \frac{SST_{n-2} + SST_{n-1} + SST_n}{3} \quad (3)$$

Where: SST_{n-2} is SST Exception Previous 2 Months;
SST_{n-1} is SST Exception Previous 1 Months;
SST_n is SST Exception Current Month;

One of the major organizations involved in global climate monitoring and forecasting, the National Oceanic and Atmospheric Administration (NOAA), uses the widely accepted and used criterion of ±0.5 ° C to assess El Nino and La Nina events.

An El Nino episode occurs when the ONI value is at or above +0.5 ° C for a minimum of five months. A La Nina event occurs when the ONI value is at or below -0.5 ° C and lasts for at least five months, according to the source (NOAA, 2025).

3.3 Data Preprocessing

The simple arithmetic average of the total number of sunspots per day for every day of a given calendar month is the monthly average number of sunspots. The number of sunspots in the source data is processed using moving average MA based on the "March combination" in accordance with the standard meteorological data processing procedure. The year, month combination, and number of sunspots are among the processed data components.

ONI downloads source data and has completed the "March portfolio" moving average MA processing. Data items include: Year, March combination, ONI.

The above two groups of data were associated with the same association condition as "year" and "March combination". Delete irrelevant data items from the results and get results that retain data from 1950 to 2024, which is called preprocessed data. Data items include: year, March combination, number of sunspots and ONI. Both sets of data have the same time dimension, allowing for charting and data correlation analysis.

3.4 Sunspot Count and ONI Charting

Using Python's matplotlib library, two sets of data are presented on the same chart. The two groups of data are visually displayed by graphical means (Figure 1) in order to find the relationship between the two groups of data. The horizontal coordinate represents the time dimension of the "March combination", the vertical axis of the principal coordinate represents the number of sunspots, and the vertical axis of the secondary coordinate represents ONI data. The red graph illustrates the variations in ONI over time, while the blue curve depicts the changes in sunspots. Two horizontal red dashed lines are shown; the El Nino threshold is at the top, while the La Nina threshold is at the bottom.

From the figure 1, we can roughly observe that when the number of sunspots is high and low, the occurrence probability of ENSO phenomenon is relatively high.

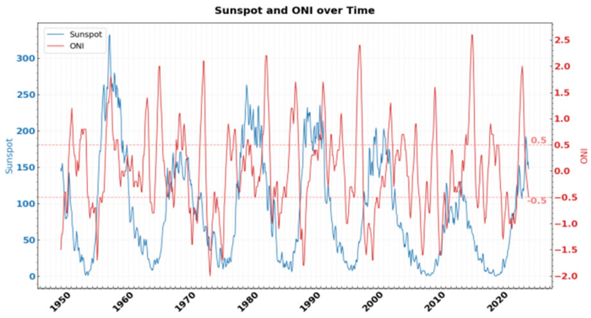

Figure 1 Number of sunspots and ONI time chart

3.5 Sunspot Number and ONI Correlation Analysis

Using Python's scipy library, the correlation between the two sets of data is quantified. The purpose is to find the strength of the correlation between the two groups of data through statistical methods. Firstly, ONI values in preprocessed data are discretized: ONI values greater than 0.5 are adjusted to 1, ONI values less than -0.5 are adjusted to -1, and ONI values between -0.5 and 0.5 are adjusted to 0. Then, the correlation strength of the two groups of data was analyzed by statistical means, as in figure 2. In the figure, the horizontal coordinate represents the number of sunspots, and the vertical coordinate represents the ONI discrete data. The correlation coefficient value of the two groups of data is 0.1209, and the p-value is 0.0003.

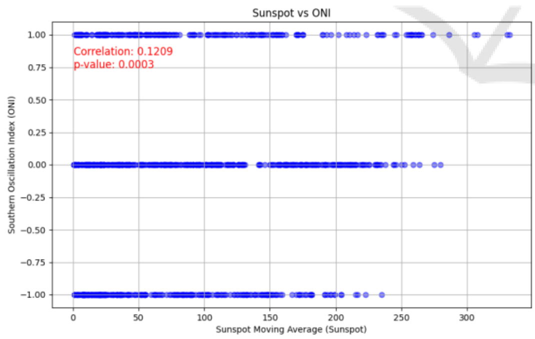

Figure 2 Analysis of the correlation between the number of black suns and ONI

Statistics show that when the P-value is very small (usually less than 0.05), it means that the null hypothesis is rejected and the correlation between the two variables is considered statistically significant. The two sets of data have a p-value of 0.0003, which is well below the cutoff point of 0.05. Consequently, it may be said that there is a correlation between the two sets of data.

A measure of the correlation between data is the correlation coefficient (r). The range of values is [−1,1]. There is no linear correlation when r=0, a totally negative correlation when r=−1, and a completely positive correlation when r=1. Although the correlation between the two data sets is small, it is positive, as seen by the two groups' r=0.1209.

4 CONCLUSION

In this paper, the association between sunspot number and ENSO data is merged, and the impacts of sunspot activity on the sun, Earth climate, and ENSO are examined and explained. The conclusion is that although sunspot activity is not the determining factor of ENSO, the two have a positive link, and the sunspot number change may be utilized as an ENSO reference factor to assist predict ENSO episodes more accurately.

ENSO is often monitored with the help of easily accessible indirect data. In addition to ONI, there are examples such as Sea Surface Temperature (SST), Ocean Heat Content (OHC), Southern Oscillation Index (SOI), and Multivariate ENSO Index (MEI) and other indicators. Due to the limited space and data acquisition methods, this paper only conducted comparative analysis of ONI data, and ONI's emphasis on the characterization of surface sea temperature in the East Pacific Ocean may weaken the driving role of OHC (Ocean Heat Content) on ENSO events. The conclusion of the data relationship has certain limitations, which cannot accurately explain the association between sunspot activity and ENSO.

At the same time, due to the limitations of research conditions, the open data of SILSO and NOAA platforms were used for analysis. Although the authority of the data was guaranteed, there were limitations. For example, differences in observation criteria between platforms (e.g., SILSO's historical sunspot count is calibrated and revised multiple times, while NOAA's ONI calculations rely on ERSSTv5 reanalysis data) can lead to systematic error accumulation across databases.

As a key disturbance source of the global climate system, ENSO affects human life, and the improvement of its prediction accuracy is of great significance to disaster prevention and reduction. Although this study is limited by the lack of data dimension and mechanism interpretation, the combination of multidisciplinary collaboration, high-precision observation and numerical simulation is expected to reveal the deep link between solar activity and ENSO, and ultimately serve a more reliable climate prediction system. If cross-platform real-time data analysis can be established in the future, it is expected to contribute to the construction of more accurate prediction models, and serve the adaptation management of human beings to extreme climates.

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